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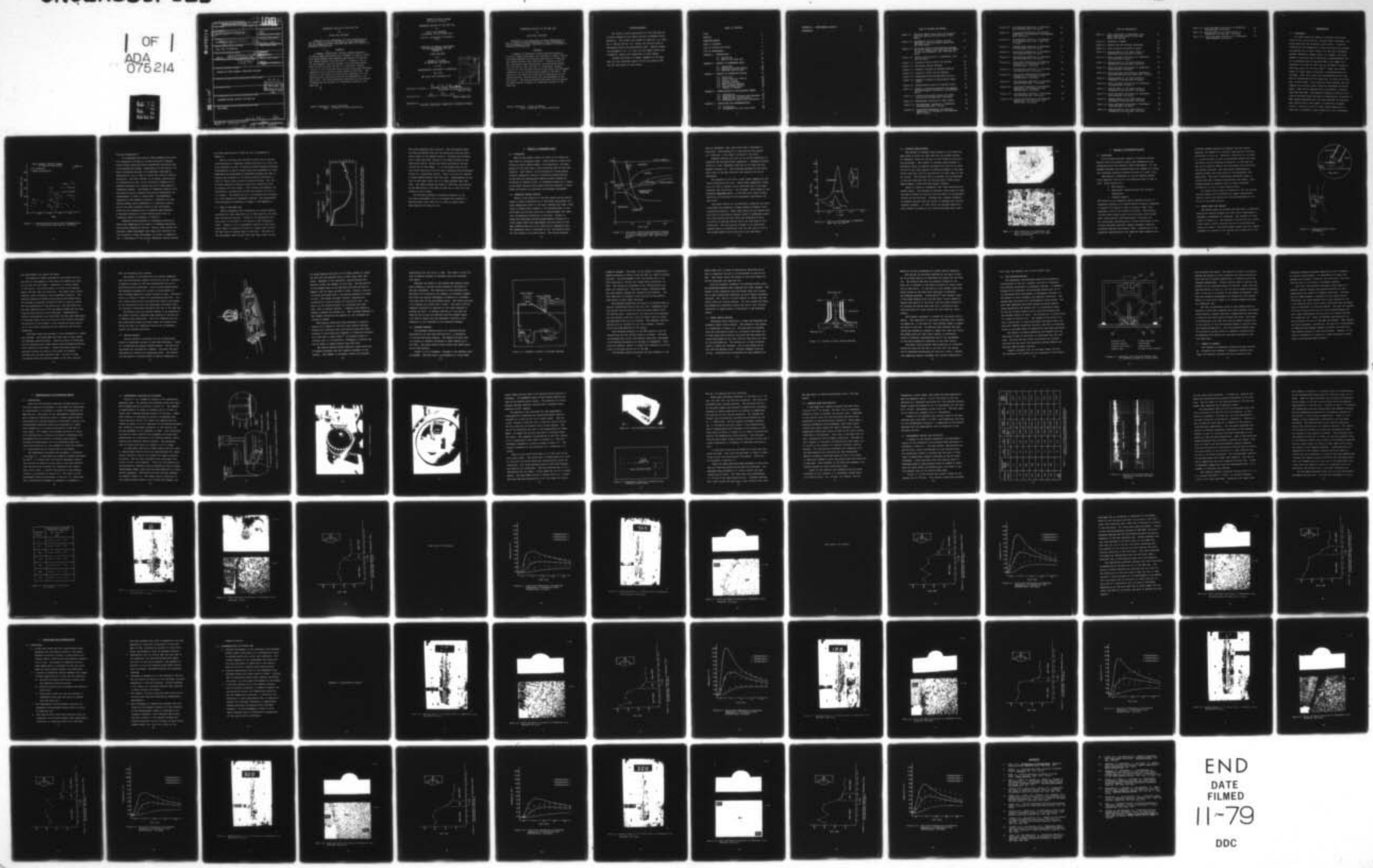

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UNDERWATER WELDING IN THE DEEP SEA

by

DAVID PAUL ERICKSON

Submitted to the Department of Ocean Engineering on May 12, 1978, in partial fuliffment of the requirements for the Degrees of Ocean Engineer and Master of Science in Mechanical Engineering.

ABSTRACT

A summary of underwater welding methods presently in use or under development are reviewed in order to determine which methods have possible application to deep sea use (depths greater than 1000 feet). Studies on one of the new methods under development (flux-shielded method) were carried out with the use of a hyperbaric chamber. A series of flux-shielded bead-on-plate welds were performed underwater up to simulated water depths of 680 feet. The quality of the welds was evaluated by examination of the macrostructure, microstructure and microhardness of the weld joint. The welds performed indicated the flux-shielded method may be suitable for underwater welding in the deep sea.

Thesis Supervisor: Koichi Masubuchi
Title: Professor of Ocean Engineering

UNDERWATER WELDING IN THE DEEP SEA

by

DAVID PAUL ERICKSON
Lieutenant, United States Navy

B.S.M.E. University of Minnesota
(1971)

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Department of Ocean Engineering
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Certified by..
Thesis Supervisor

Accepted by...
Chairman, Department Committee on Graduate Studies

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

LIST OF PHOTOGRAPHS

1. INTRODUCTION

1.1 BACKGROUND

In recent years the number of offshore structures; including oil drilling rigs, storage tanks, pipelines, etc., being installed has increased significantly. Costs for construction and operation of these structures are increasing rapidly due to their larger size and their placement farther offshore in deeper water. For example, the total number of drilling rigs in the world is approximately 400. It is estimated that by the mid-1980's the number will increase to as high as 1000 rigs and estimates as high as 1600 rigs exist for the year 2000.[2] These rigs consist mostly of three types; drillships, semisubmersibles and jack-ups. Most drill ships and semisubmersibles are capable of performing drilling operations in water up to 1000 feet in most cases. Drill ships do exist however that are capable of drilling in what could be considered unlimited depth. Most of the jack-up drill rigs operate in waters less than 400 feet. The operation depths of jack-up drill rigs is plotted versus the year of construction in Figure 1.1. This figure indicates that the trend has been to construct more jack-up drill rigs capable of operating in deeper waters. A jack-up rig with a water depth capability of 3000 feet is presently under construction for a Norwegian

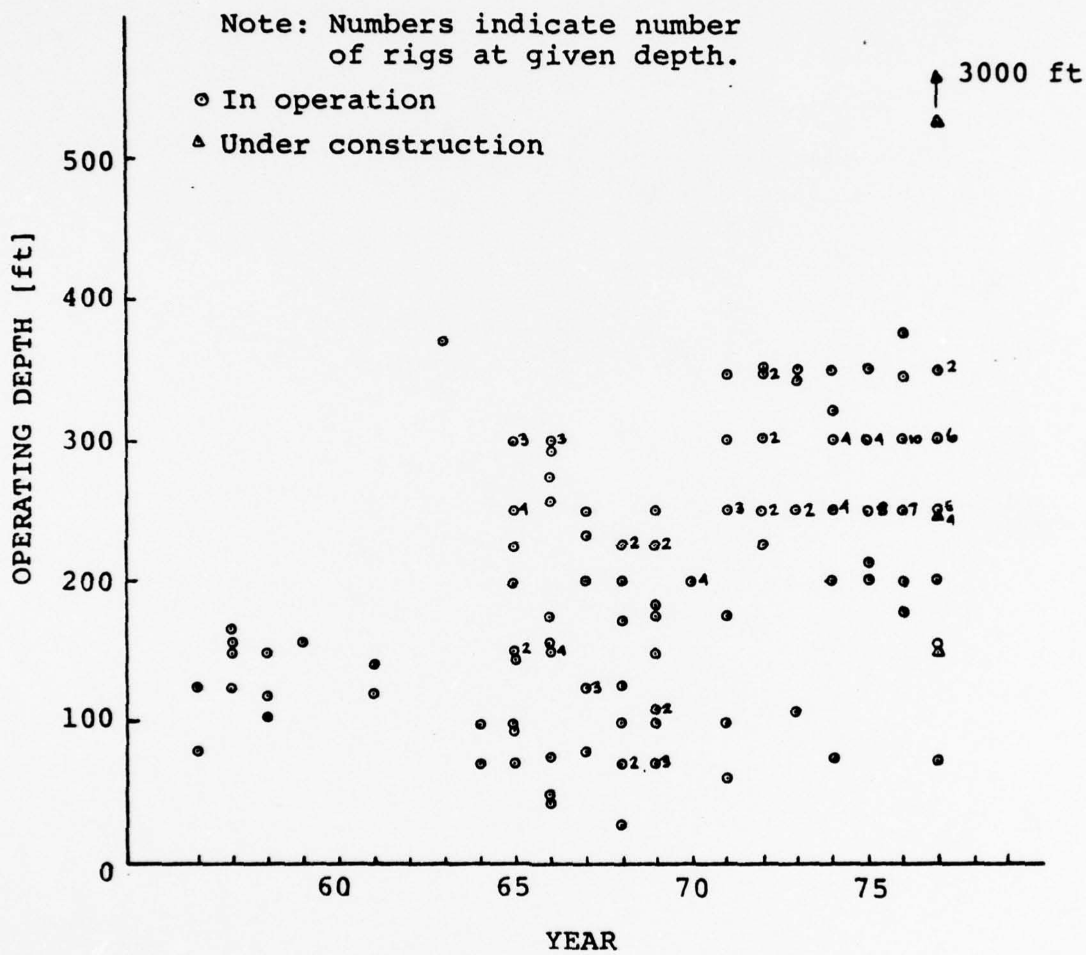


Figure 1.1 Operating Depth versus Year of Construction for Jack-up Drilling Rigs in the World.

drilling corporation.[2]

It is expected that some of these offshore structures will experience failures of various structural elements during normal usage and during unpredicted occurances such as collisions and storms. Additionally in the future, offshore structures may want to be modified, relocated or fabricated at sea in order to reduce the costs of offshore operations. Any work, whether it be repair, modification or construction at sea, on the structural elements of an offshore structure will require the use of some method of underwater welding. Any method of underwater welding to be used must be able to produce high quality welds which are reproducable in order to insure safe, long, dependable operation of the offshore structure. Production of high quality welded joints underwater is a difficult problem due to the rapid quenching effect of the surrounding water and the susceptibility to hydrogen embrittlement. A detailed discussion of weld defects which occur in underwater welds is presented in Chapter 2.

Presently several methods of underwater welding are being used commercially for repair of offshore structures with varying degrees of success. Several other methods are presently under development which show good potential but are too early in their development to be put to commercial use. A discussion of the various underwater welding methods

and their application to deep sea use is presented in Chapter 3.

Much of the work that has been carried out by various investigations on underwater welding has been of a trial and error approach in order to hastily develop workable processes. Investigators at MIT in recent years have attempted to first understand the mechanisms of underwater welding and then to develop new processes or to improve existing processes in order to obtain better quality underwater welds. The flux-shielded underwater welding process was conceived at MIT by applying this philosophy. This process was selected for experimental investigation because the process is still in its infancy. The method has yet to be proven fully feasible as a valid method for underwater welding. The experimental work performed is presented in Chapter 4 and Appendix A.

1.2 WHAT IS THE DEEP SEA?

Before proceeding into discussions of various welding processes and their applicability to deep sea use, the term deep sea must be defined. Presently all significant off-shore work is performed in the waters of the continental shelf. Figure 1.2 is a diagrammatic profile of the conti-nental shelf is generally defined as a depth limit of 850-900 feet with an average depth of 400 feet. The width of the continental shelf varies from less than a mile to over

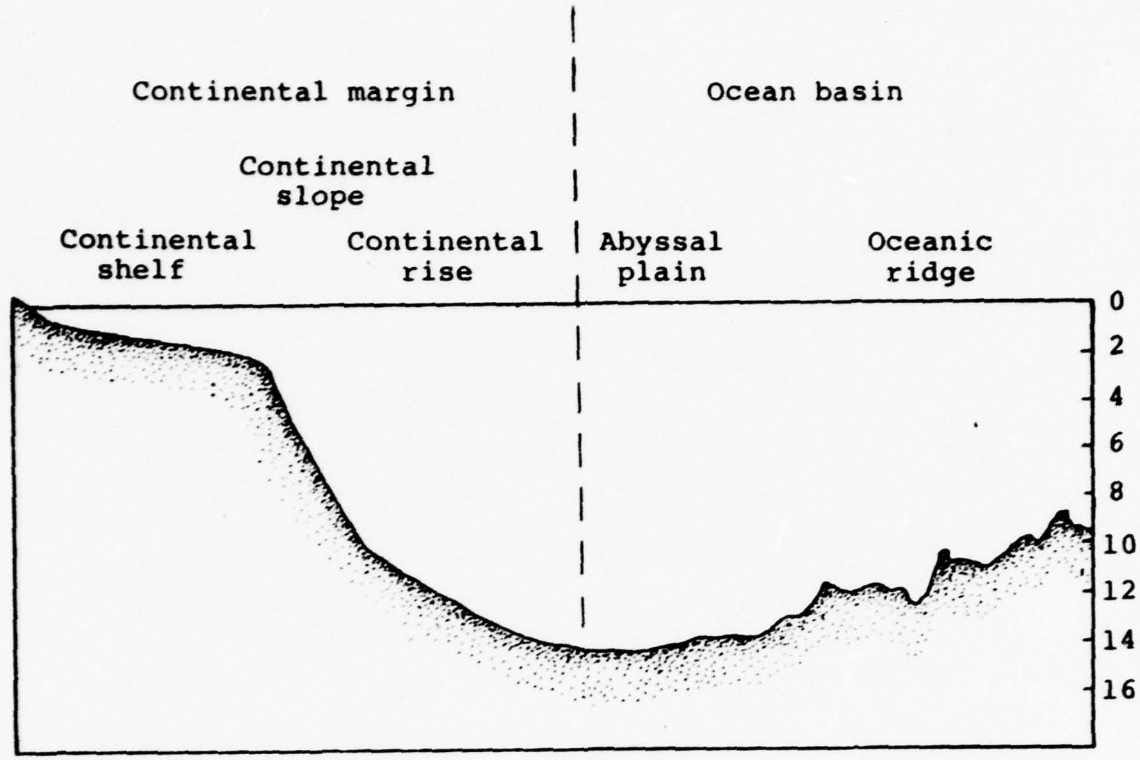


Figure 1.2 Diagramatic Profile showing the main features of the Continental Margin and the Ocean Basin.[1]

800 miles depending upon location. The continental shelf and the continental rise are the transition from the continental shelf to the abyssal plains. Although most offshore work to date has been limited to the deeper waters of the continental shelf, seismic petroleum exploration has been carried out on the slopes. It is envisioned that in the near future drilling rigs will begin exploring the continental slopes to a significant degree. These rigs will all operate in water depths greater than 1000 feet. Approximately 85 per cent of the ocean floors are at a depth greater than 1000 feet. For these reasons the depth of 1000 feet was selected as the definition of the deep sea for use in the title and context of this thesis.

The various underwater processes presently in use and under development will be discussed with respects to depths greater than 1000 feet in order to access their applicability for deep sea use.

2. DEFECTS IN UNDERWATER WELDS

2.1 BACKGROUND

Many of the defects which are found in air welds are also found in underwater welds. These defects include such things as strike embrittlement, low penetration, non-homogeneity of the weld metal, slag inclusions and hot and cold cracking. Weld defects can be divided into three general classes; dimensional defects, structural discontinuities in the weld and undesireable defective metal properties. Virtually all defects found in underwater welds are a result of two basic factors which result from the presence of water. These two factors are quenching and hydrogen entrapment.

2.2 QUENCHING INDUCED DEFECTS

Water in the vacinity of the weld region during welding leads to rapid solidification of the molten weld mental and rapid temperature drops in the heat attected zone (HAZ). This leads to undesireable changes in the microstructure in the weld metal and the HAZ resulting in embrittlement and reduction in mechanical properties of the weld. Figure 2.1 shows the continuous cooling transformation diagram for a 0.17% carbon steel with approximate cooling rates for the heat affected zone for an air weld and an underwater weld. The underwater weld is performed in the 'wet' meaning water has free access to the weld region. The curves indicate

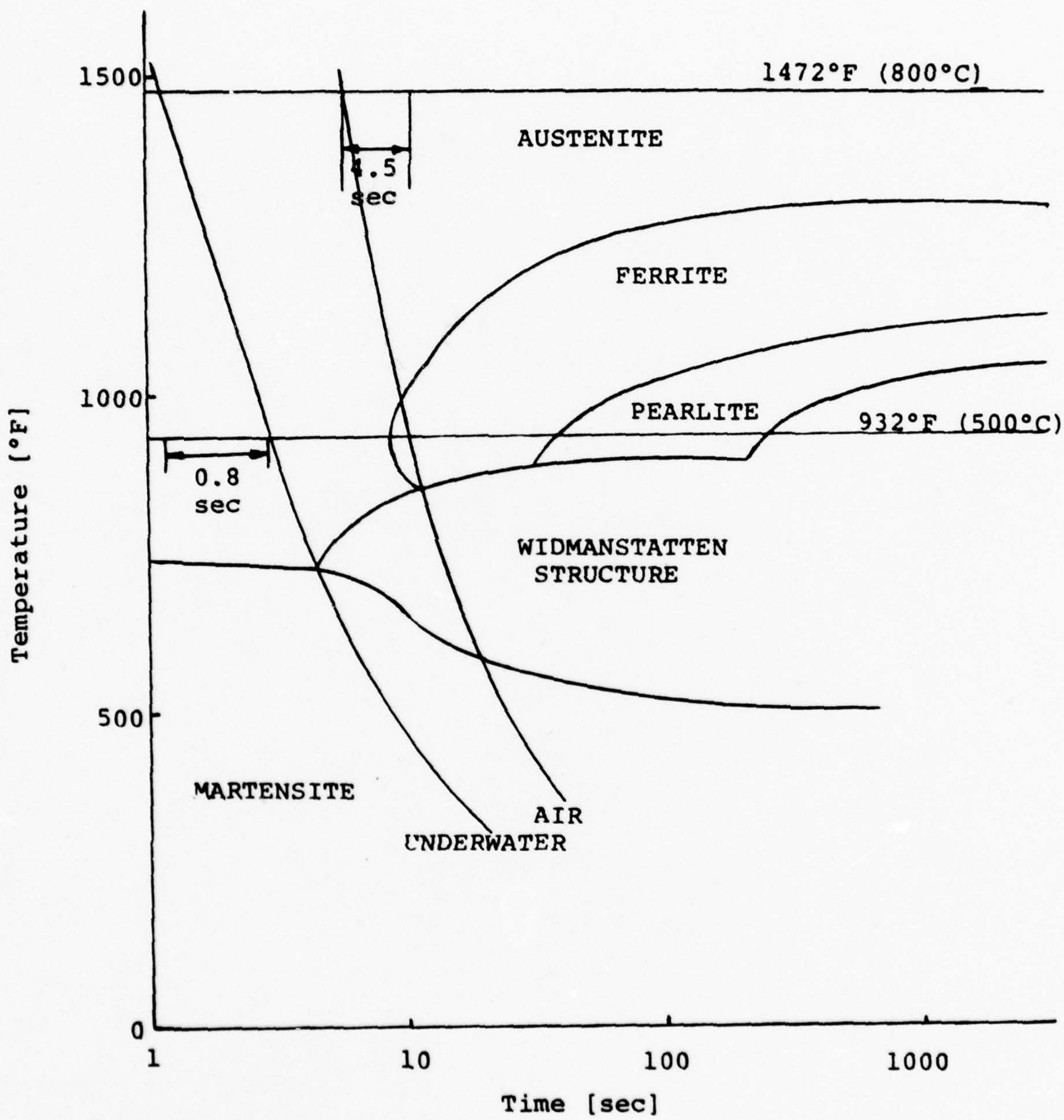


Figure 2.1 Continuous Cooling Transformation Diagram for 0.17% Carbon Steel with Cooling Rates of HAZ[19] for Underwater 'Wet' Weld and Air Weld.

that an underwater 'wet' weld would have a martensitic structure. This martensite is very brittle and results in a reduction in the impact strength of the joint.

Hardness readings are used as one of the indicators to indentify the microstructure composition. Hardness distributions in a 'wet' underwater weld and an air weld are presented in Figure 2.2. The increased hardness of the underwater weld in the HAZ indicates the presence of brittle martensite.

The presence of the water causes steep temperature gradients surrounding the weld. These steep temperature gradients can lead to thermal stress build-ups due to the rapid expansion and contraction. The stresses which maybe of considerable magnitude remain in the weld joint after cooling resulting in distortion of the base metal surrounding the weld joint.

The rapid cooling of the weld metal caused by the water can prevent the escaping of gases formed by chemical reactions during welding. These gases which can not escape form the voids or gas pockets commonly found in underwater welds. The rapid cooling may also cause the formation of slag inclusions in welding methods which use some type of flux protection. The slag becomes trapped in the weld metal because there is insufficient time for the slag to rise to the surface before solidification of the weld metal.

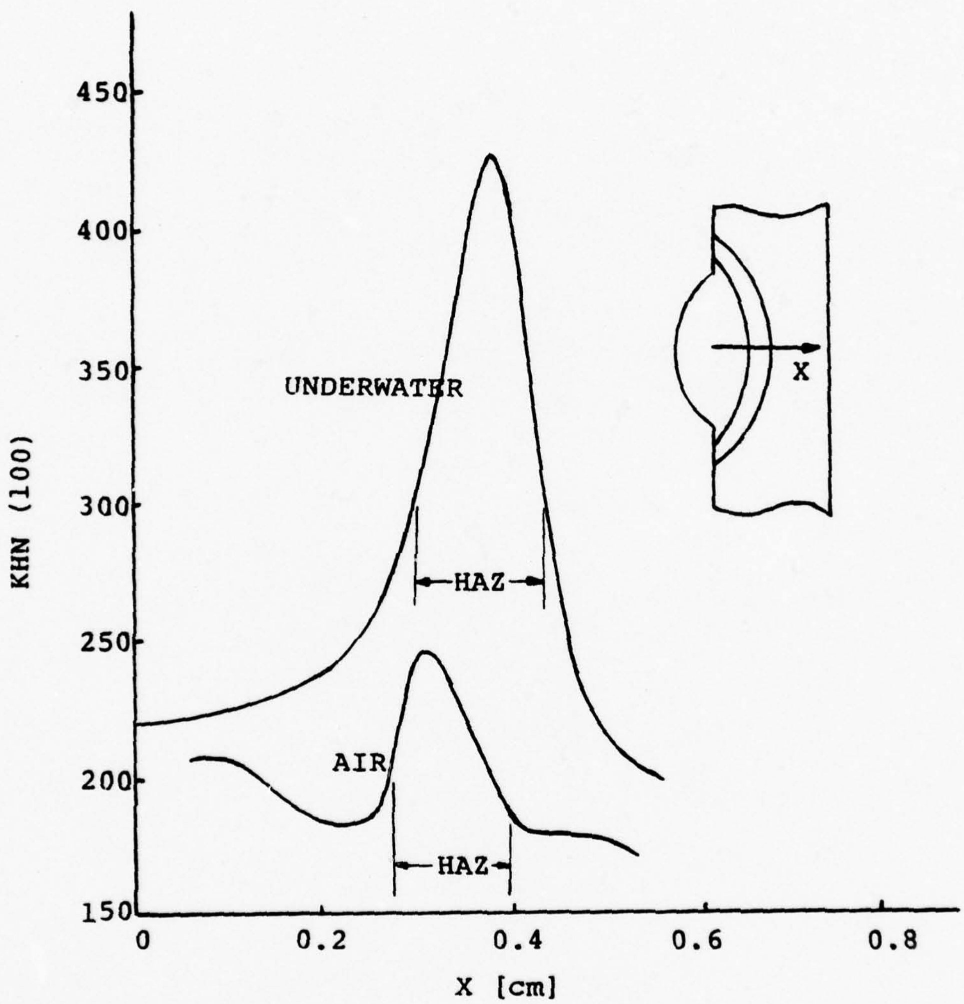
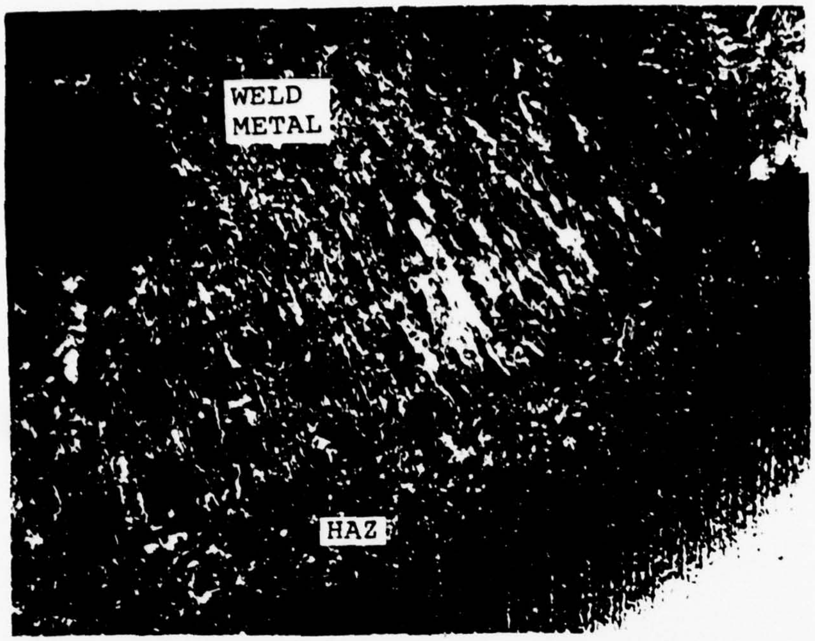


Figure 2.2 Hardness Distribution in Underwater 'Wet' and Air Weld.[18]

2.3 HYDROGEN EMBRITTLEMENT

The problem of hydrogen embrittlement in air welds has been known to exist for some time and the problem reduced to reasonable limits by the use of such things as low hydrogen electrodes. The problem of hydrogen embrittlement in underwater welds is greatly increased over that of air welding due to the large amounts of hydrogen present in the weld region resulting from the dissociation of water vapor in the arc region. The hydrogen which is present can be dissolved in the heat affected zone and the weld metal which causes embrittlement, cracks and microscopic fissures.

Photo 2.1 shows an underwater 'wet' weld containing hydrogen cracks. The presence of hydrogen cracks such as these can grow in steps to critical size and result in catastrophic failure of the structure. Hydrogen has a greater tendancy to promote cracking when the region is hardened and contains residual stresses. In other words the hydrogen embrittlement problem increases as the quenching becomes more rapid.



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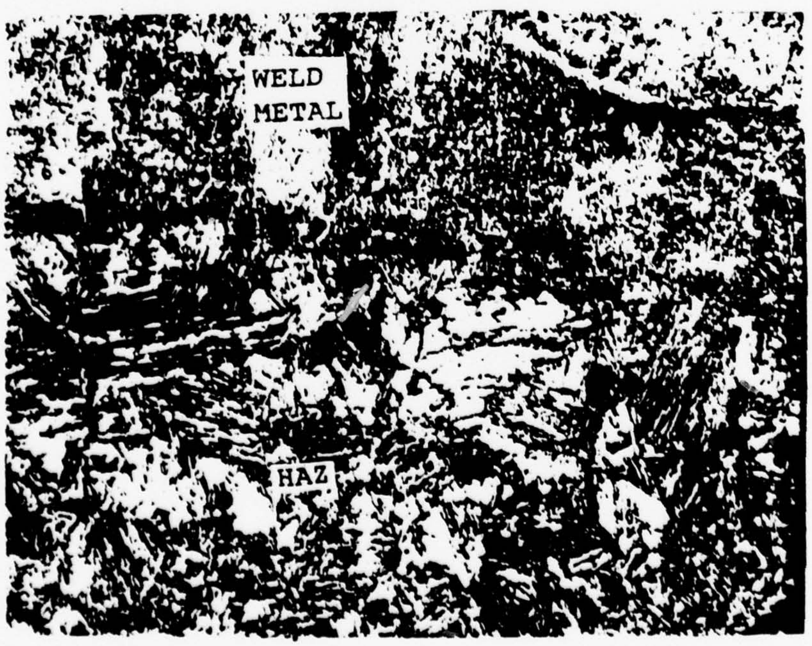

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Photo 2.1 Microstructures of Underwater 'Wet' Weld containing cracks in the Weld Metal and the HAZ.

3. METHODS OF UNDERWATER WELDING

3.1 BACKGROUND

The following sections summarize underwater welding methods which are presently being used commercially and techniques which are presently under development. All the methods discussed are processes which are capable of joining two structural elements together by means of a metal joint.

When making a comparison of various welding methods three important factors for the comparison have to kept in mind. These factors are:

1. Weld quality,
2. Operational characteristics and technical feasibility,
3. Economic aspects.

Weld quality is an important factor because the goal of underwater welding is to achieve welds of quality comparable to those of air welds in order to obtain a safe, long dependable life of the offshore structure. Weld quality includes such things as weld joint strength, notch toughness, weld porosity, weld penetration, cracking, etc. The operational characteristics include such things as the welding equipment required, support equipment required, personnel required and welding times. Examination of the operation characteristics are important when comparing the

different methods because the simplier and more easily adaptable the method is to differnt applications, the more advantagous it will be. Technical feasibility is included as a factor because it must be determined whether the welding method can be performed successfully in the deep sea due to the physical effects the enviroment has on the welding process involved. The operational characteristic directly affect the third factor to be considered, that being cost. The cost of performing underwater welds is usually high and increses significantly with depth. Some methods become so expensive that it makes the method prohibitive to use in certain applications.

All three factors must be examined for all the welding methods because certain methods may appear advantageous based on one or two factors but be disadvantageous on one or two of the other factors.

3.2 MANUAL METAL ARC WELDING

The manual metal arc process has been used in underwater welding for several decades with very little improvement in equipment, consumables or technique. The process is illustrated in Figure 3.1. The welding is carried out by a diver/welder using a stick electrode much as he would when performing air welds. The welding power supply and life support equipment are located on the surface with connection to the

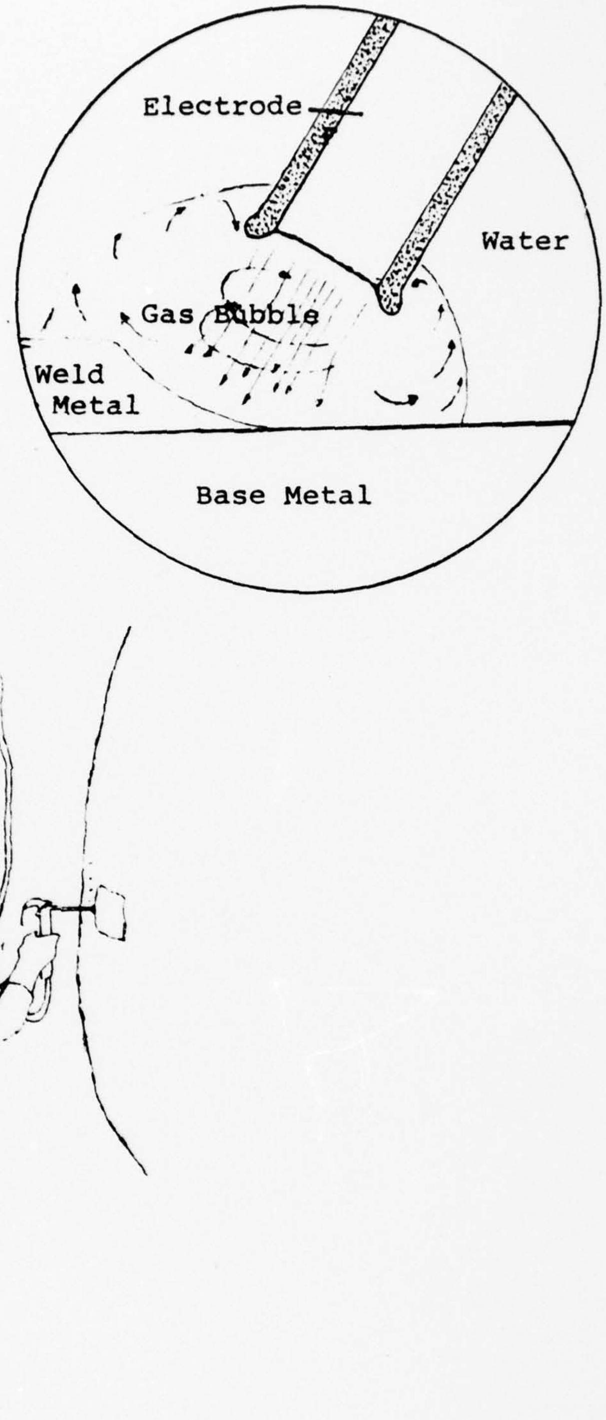


Figure 3.1 Underwater Manual Metal Arc Welding.

the diver/welder via cables and hoses.

The quality of welds produced by this method are very poor due to the presence of the water surrounding the welding arc and the weld metal. Martensite is always formed at the fusion line which results in ductility of approximately 50% that open air ductility. The welds often contain undercut, slag inclusions, and considerable porosity. The tensile strength of welded joints made by the manual metal arc process is generally around 80% that of open air welds. The only protection to the welding arc, the weld metal and the heat affected zone is the gas bubble formed and the slag from the flux coating on the electrode. Experiments by several investigators have shown that the best weld appearance is obtained using rutile or acid/iron oxide coated electrodes. The addition of iron powder to the coating and water proofing of the coating improves the arc stability and the weld appearance.

The manual metal are process is very susceptible to hydrogen cracking. Two electrodes have been used to help reduce the hydrogen cracking proble. These are ferritic electrodes with an oxidizing iron oxide coation and electrodes producing fully austenitic weld metal. These electrodes reduce the hydrogen cracking by reducing the amount of hydrogen deffused into the heat affected zone. The use of these electrodes helps but hydrogen damage to the heat affected

zone is invariably still present.

The quality of the welds are also greatly dependant upon the diver/welders comfort and ability to see. Welding in depths in excess of 200 feet necessitates the use of saturation diving techniques. This involves sophisticated and expensive equipment but allows the diver/welder to work at deeper depths for longer periods of time. Saturation diving is limited to depths of approximately 900 feet. For this reason combined with the additional safety risk placed on the diver/welder with increasing depth the manual metal arc process is considered infeasible for use in the deep sea.

The manual metal arc process however is an inexpensive and highly versatile technique when welding is carried out in shallow water operations. This fact combined with the poor weld quality make the manual metal arc process best suited for work of a temporary nature such as emergency repairs and salvage operations.

3.3 HABITAT WELDING

Habitat welding is probably the most sophisticated method of underwater welding to have been developed. Figure 3.2 illustrates the habital welding method. The work area and welder are enclosed by a chamber. The water has been displaced by a mixture of pressurized gases. This method has the ability to produce welds of quality comparable to

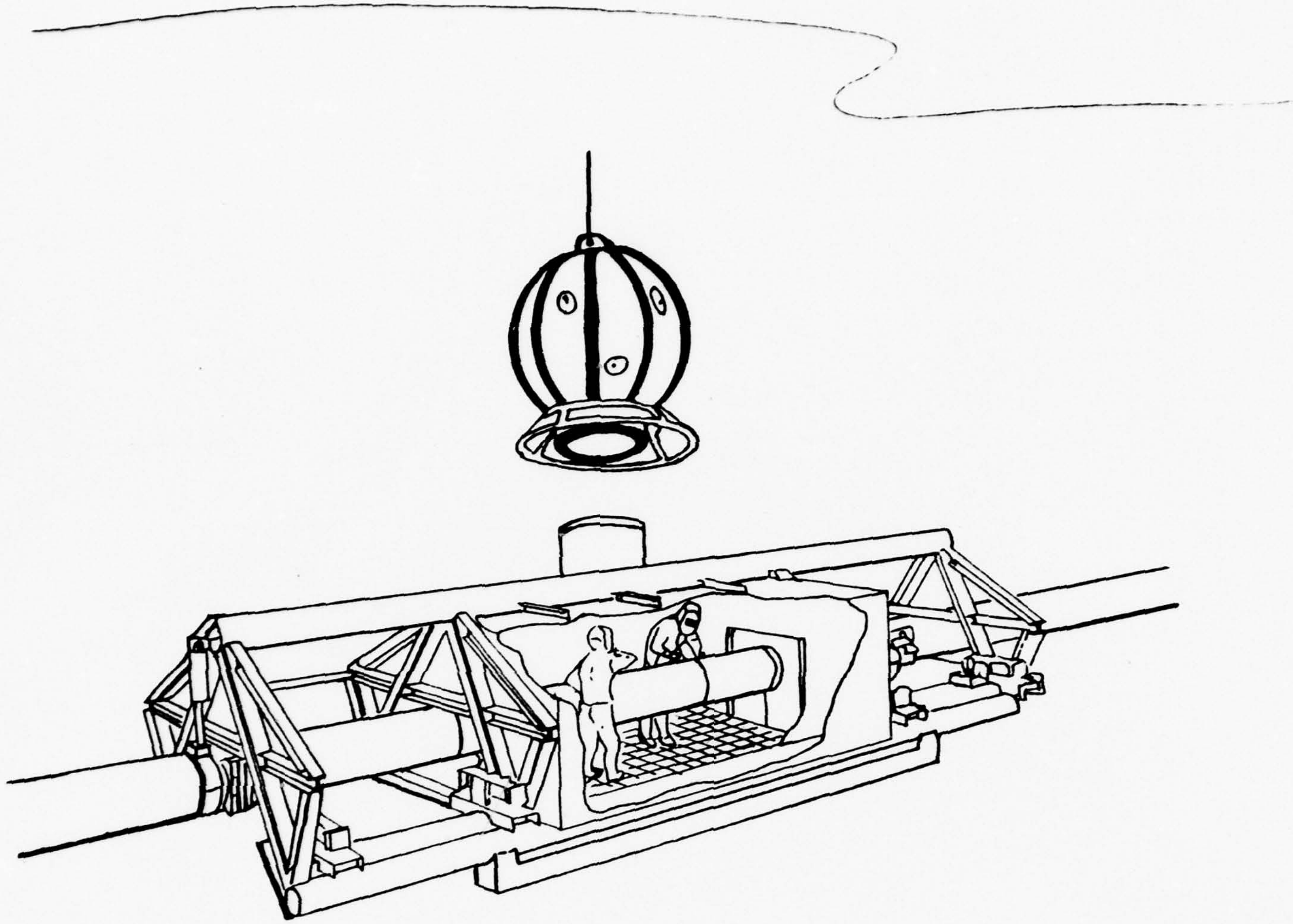


Figure 3.2 Underwater Habitat Welding.

air welds because the water is no longer present to quench the weld and the hydrogen level is much lower than 'wet' welds. Hydrogen is not completely removed because the humidity within the chamber is very high. The gas mixture in the chamber must not be explosive and must be able to support life for short periods of time. Usually a mixture of helium and oxygen with a low partial pressure of oxygen is used. The welder breathes through a seperate gas system which is more suitable for sustaining life. Gas metal arc and tungstein metal arc processes have both been used in habitat welding. A seperate gas system is needed to shield the welding arc. The increased pressure in the chamber constricts the welding arc and increased arc voltage is needed.

Code quality welds have been performed on pipeline repairs up to depths of 400 feet using habitat welding. Studies have indicated that good quality welds have been produced in gas pressurized chambers in simulated pressures up to 950 feet of water depth.[8] No evidence exists to indicate that it is technically infeasible to perform GMA and TIG welds at depths greater than 1000 feet.

The habitat welding method requires large quantities of complex equipment and much support equipment on the surface. The chamber is extremely complex and designed

specifically for one job at a time. The result is that the cost of habitat welding is extremely high and increases with depth.

Exposing the welder to the pressurized gaseous atmosphere presents a serious safety problem as the depth of the work increases. Two solutions to this problem exist. The first is to construct the chamber as a pressure chamber and allow the gaseous atmosphere to operate at a pressure less than that of the surrounding water. The second solution is to replace the welder with a robot. The robot could be computer controlled to perform all the tasks required to perform the weld. If habitat welding is to be used for deep sea use it must be modified from the present operation used to insure that any personnel involved in the operation is not subjected to any excessive dangers.

3.4 HYDROBOX WELDING

The hydrobox welding mentod is a patented process developed by the Sub Ocean Services Ltd., a subsidiary of the British Oxygen Company. The method has been used for repairs on offshore platforms in water depths up to 120 feet. Sub Ocean services make claims that these welds are of code quality.

Figure 3.3 is a schematic diagram of the hydrobox welding method. The weld area is surrounded by a tailor-made

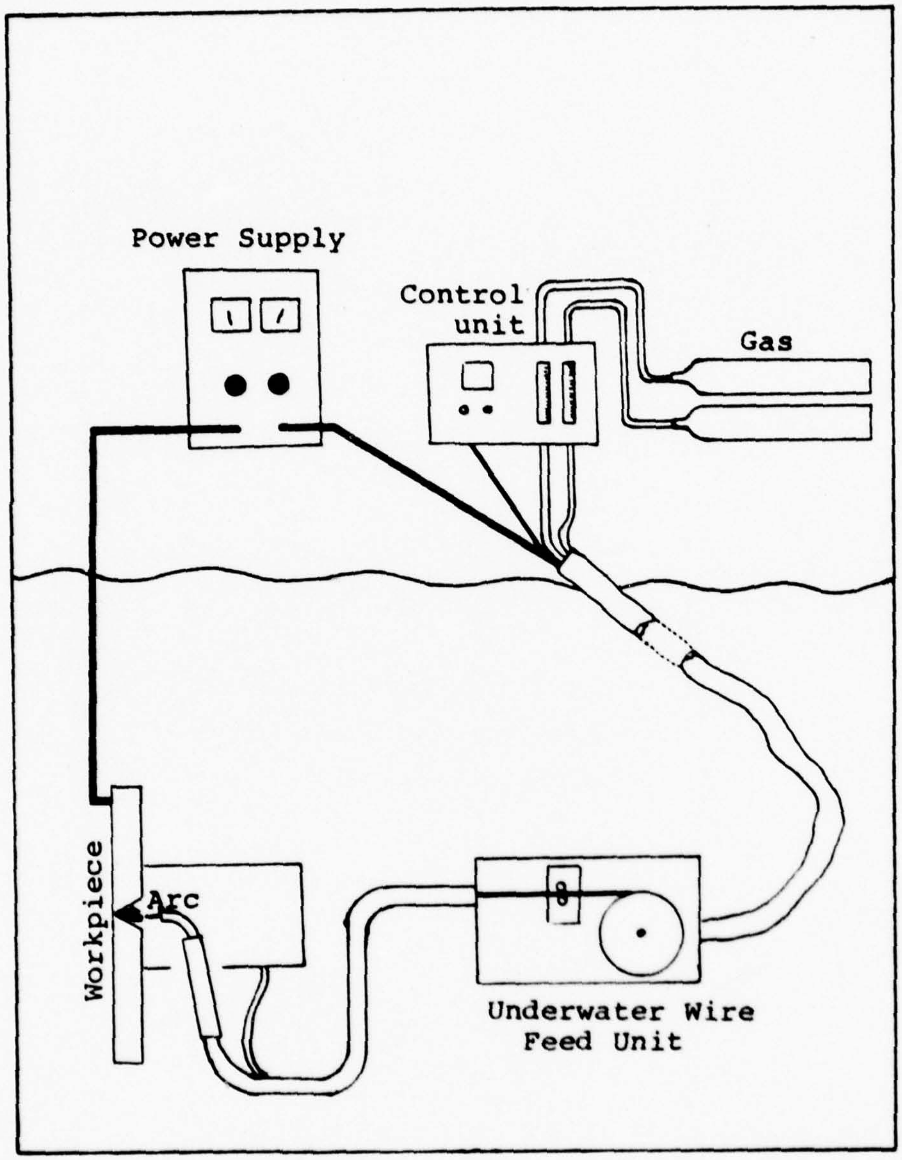


Figure 3.3 Schematic Diagram of Hydrobox Welding.

canopy of penspex. The water in the canopy is displaced by gaseous mixtures to form a local dry spot in order to perform the weld. The diver/welder holds the welding gun in his hand and places it within the conopy while performing the weld. The welding is performed using a semiautomatic gas metal arc welding gun. The power supply, shielding gases and life support systems are located on the surface. The wire feed unit is located in the vacinity of the welding area within a water tight container.

The hydrobox method has the ability to produce welds of quality considerably better than any 'wet' underwater welding process used because the water has been removed from the welding area. Quenching of the weld will be eliminated but the cooling rates will still be faster than air welds and martensite may still be present. The hydrogen cracking problem will be reduced but can still present a problem due to the high humidity in the canopy.

The increased pressure on the GMA results in the arc constricting and the voltage tends to increase. Although the pressure does effect the welding conditions, adjustment in the welding parameters can be made it compensate. Thus from the technical aspect it seems to be feasible to perform welds in the deep sea by use of the GMA.

The hydrobox method possesses the same drawback as the

manual metal arc in terms of operational characteristics, that is requiring the use of a diver/welder to perform the weld. The diving limits and safety of the diver deems the method unsuitable for deep sea use.

From the economic standpoint the hydrobox method could be considered moderate when compared with other methods. The method is more expensive than the manual metal arc process due to more preparation necessary and more support equipment required. The quality of welds however is better than the manual metal arc process however. For this reason the hydro-box method will gradually replace the use of 'wet' welding techniques in repairs made to structures in the shallower waters.

3.5 WATER CURTAIN WELDING

Mitsubuchi Heavy Industries in Japan has developed the automatic water curtain method. The concept of the method is illustrated in Figure 3.4. The weld area is shielded from the surruounding water by a divergent ring water jet of high speed which entrains the water and gas inside the region surrounded by the flow. The jet flow acts as a wall by its high momentum. The welding arc is thus contained within a stable gas envelope. One or more gases can be fed into the welding torch. The most commonly used gas is CO_2. Continuous wire electrodes are used enabling the

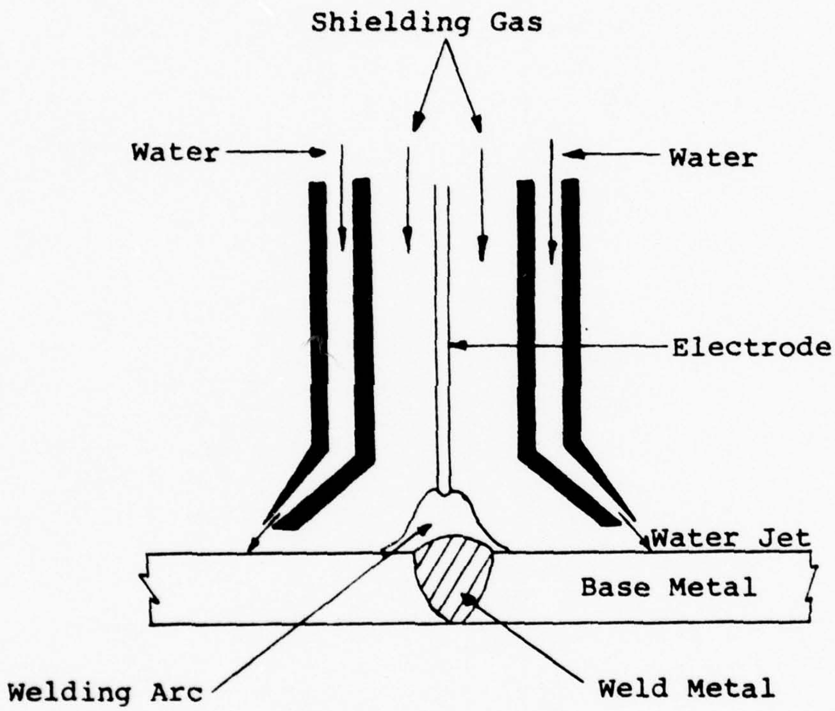


Figure 3.4 Concept of Water Curtain Welding.

method to be fully automated for remote control operation.

The quality of the welds produced by the water curtain can be of good quality if conditions are proper for the welding. The welding head must be properly aligned for the water jet to impinge on the plate correctly to insure formation of the cavity. If the cavity is not formed water has direct access to the weld area resulting in quenching and hydrogen problems. Investigators[19] have recently used a flux-cored welding wire with the water curtain method to improve the quality of the welds. The flux adds protection by covering the molten weld pool with a protective slag covering which will help isolate the weld from any water present.

Much support equipment is needed for the water curtain method. The complexity of the system increases with increasing depth due to the need for high pressure pumps to supply the water to the jet. In addition high pressure and high volume gas systems are needed to supply the inner gas cavity. The method does not lend itself readily to performing welds of different configurations due to the impingement on the plate needed for formation of the local cavity.

The water curtain method shows potential as a possible method for deep sea use due to the fact that the system can be automated,eliminating the need for a diver. However the compicated support equipment and limited configuration

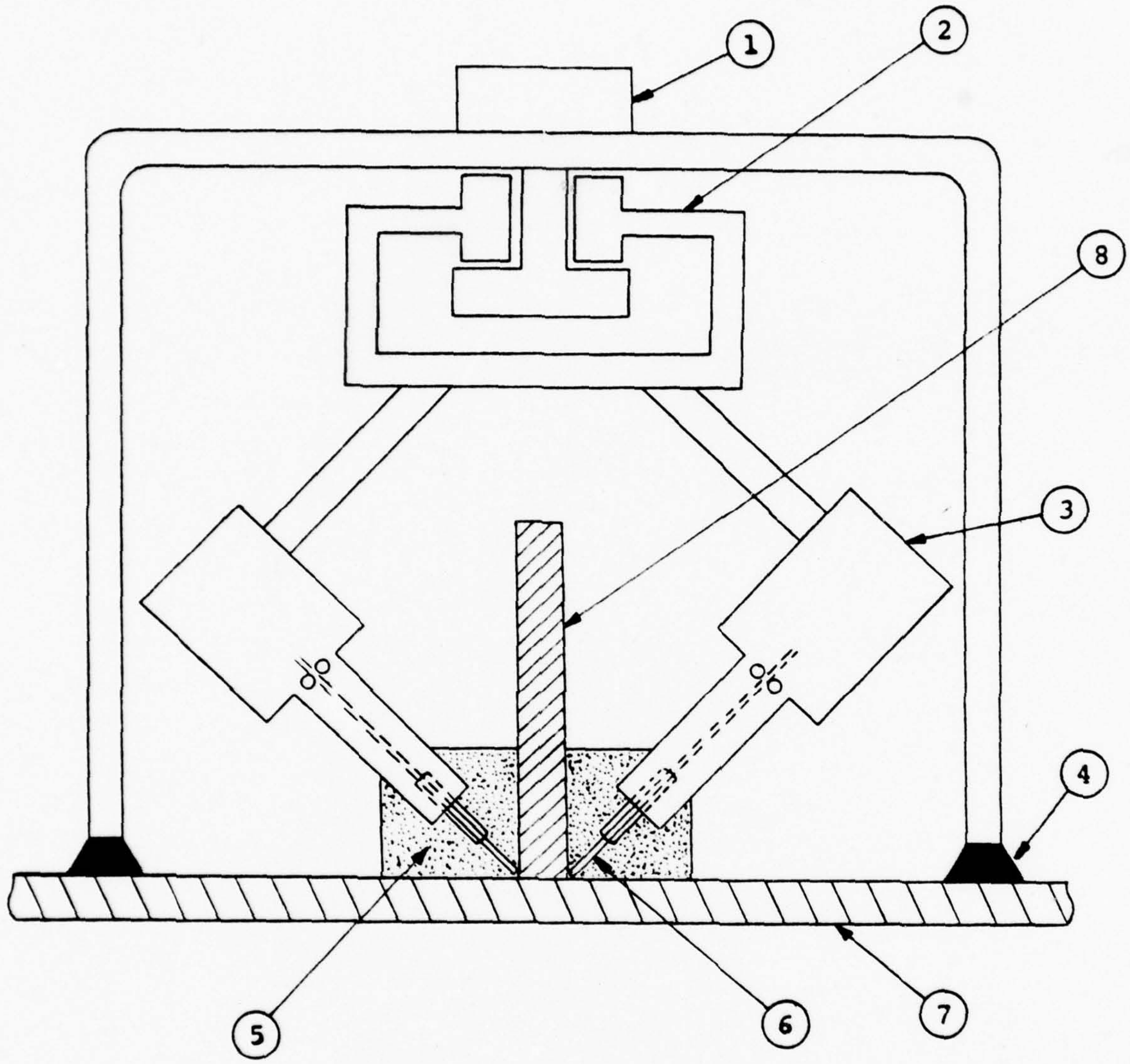
will limit the method's use to only certain jobs.

3.6 FLUX-SHIELDED WELDING

The underwater flux-shielded method was conceived by investigators at MIT as a possible solution to eliminate the problems encountered in underwater welding. A schematic diagram of an underwater flux-shielded welding unit as it is envisioned after development is presented in Figure 3.5. The method is fully automatic and remotely controlled. The system uses continuous wire electrodes as filler metal. The wire feed mechanism and travel system are water proofed. After positioning the welding unit is evacuated of water by the use of high pressure gas to help the welding from the adverse effects of water. The welding arc is struck within a layer of welding flux. The purpose of the flux is to form a molten pool of slag surrounding the molten metal and weld area thereby protecting the weld. The flux is contained within a cartridge which is replaced for each weld performed.

The quality of welds produced by this method could be very good if most of the water is eliminated from the weld area. The flux and gas within the welding unit protect the weld and weld area from quenching induced defects and hydrogen embrittlement problems.

Support equipment such as the power supply and gas are located on the surface and are connected to the welding



1-Control box	5-Flux cartridge
2-Travel system	6-Electrode
3-Wire Feed system	7-Base plate
4-Water seal	8-Plate to be attached

Figure 3.5 Underwater Flux-Shielded Welding Unit for attaching a plate on a flat object.

unit by hoses and cables. The need for a diver is eliminat- because the system is fully automatic and could be positioned by the use of manned submersibles or remotely controlled unmanned submersibles. Divers could be used to position the welding unit in shallower waters if desired. Since the flux-shielded method is still in its very early stages of development it has yet to be proven if the method is feasible. Much work and technical development are needed with this method before it could prove itself as a reliable method available for commercial use.

The cost of performing welds by this method would be moderate to high when compared with other methods. The method would require a support ship and a submersible for operation in deep sea use which would increase the costs. The costs are envisioned to be less than that of habitat welding due to the ability of the flux-shielded method to perform welds with minimum preparation. The flux-shielded method could be utilized to perform welds of different configurations by modifying the welding unit and flux cartridge to suit the conditions.

3.7 SUMMARY OF METHODS

Five methods of underwater welding have been discussed. Although other methods of underwater welding exist these five methods represent the major portion of the

underwater welding performed commervially and of research by various investigators. An examination of these five methods with respect to deep sea use indicates a void and a need for work in the field of underwater welding.

The first three methods discussed, manual metal arc welding, habitat welding and hydrobox welding are used commercially for repair of offshore structures. Although each of these methods is suitable for use under certain conditions, all three methods show little promise for use in the deep sea due to diver depth limitations and increased risks to presonnel at increased depths. The last two methods, the water curtain method and the flux-shielded method are still under development and have yet to be proven feasible for commercial use. These two methods show potential as being suitable for use in the deep sea however. Both methods are fully automated, eliminating the need for a diver/welder. In addition both methods attempt to protect the weld area from adverse effects by removing the water. Removal of the water is essential to elimiate or reduce quenching induced defects and hydrogen embrittlement.

4. INVESTIGATION OF FLUX-SHIELDED METHOD

4.1 INTRODUCTION

Since the flux-shielded underwater welding method is in its early stages of development it was chosen for experimental investigation in an effert to assess its feasibility for deep sea use. The intent of the experimental investigation was to simulate conditions similar to those which would be encountered by a welding machine as described in Section 3.6. Flux-shielded underwater welds were performed in a hyperbaric chamber up to a pressure equivalent to 680 feet of water depth. The chamber was designed and built to assist MIT investigatiors in evaluation different underwater welding methods and the effects of pressure upon welding. Although the experimental work was performed under very controlled conditions it was intended to study the feasibility, characteristics and limitations of the method.

The experimental procedure and equipment is presented in Section 4.2. A semi-empirical computer analysis developed by Tsai[18] to analyze heat flow during underwater welding was utilized to predict cooling rates in the heat affected zone and specified locations for comparison with experimental data taken. A general description of the computer analysis is presented in Section 4.3. The result of the experimental work are presented in Section 4.4. Additional data, pictures and diagrams are presented in Appendix A.

4.2 EXPERIMENTAL PROCEDURE AND EQUIPMENT

Figure 4.1 is a schematic diagram of the experimental apparatus used. All welding was preformed inside the hyperbaric chamger which is pictured in Photo 4.1. The chamber is approximately 30 inches in diameter and 4 1/2 feet in length with a maximum working pressure of 300 psig. Underwater welding is performed by placing a plexiglass tank containing water inside the chamber and pressurizing the chamber by means of an air compressor to the desired pressure. The welding is performed underwater in the tank but the welding equipment is not immersed in water. This eliminates the need for water proofing the equipment and allows easy modification for investigation of different welding configurations and different welding methods. The plexiglass tank is filled with water to a depth of 5 to 6 inches.

An AIRCO MIGet Welding Gun Model AH20-E with Air comatic Control Model AHC-M/S which has been modified for remote control operation outside the chamber was used to perform the welds. The gun uses consumable wire electrodes from 0.030 to 0.045 inch diameter. Travel for the welding gun was provided by a Welding Tooling Corporation Bug-O Carrage (Experimental Model) which had also been modified for remote control operation. The welding gun and carriage assembly are shown in Photo 4.2. The remote control operation of this system allows welding to be started and stopped, and

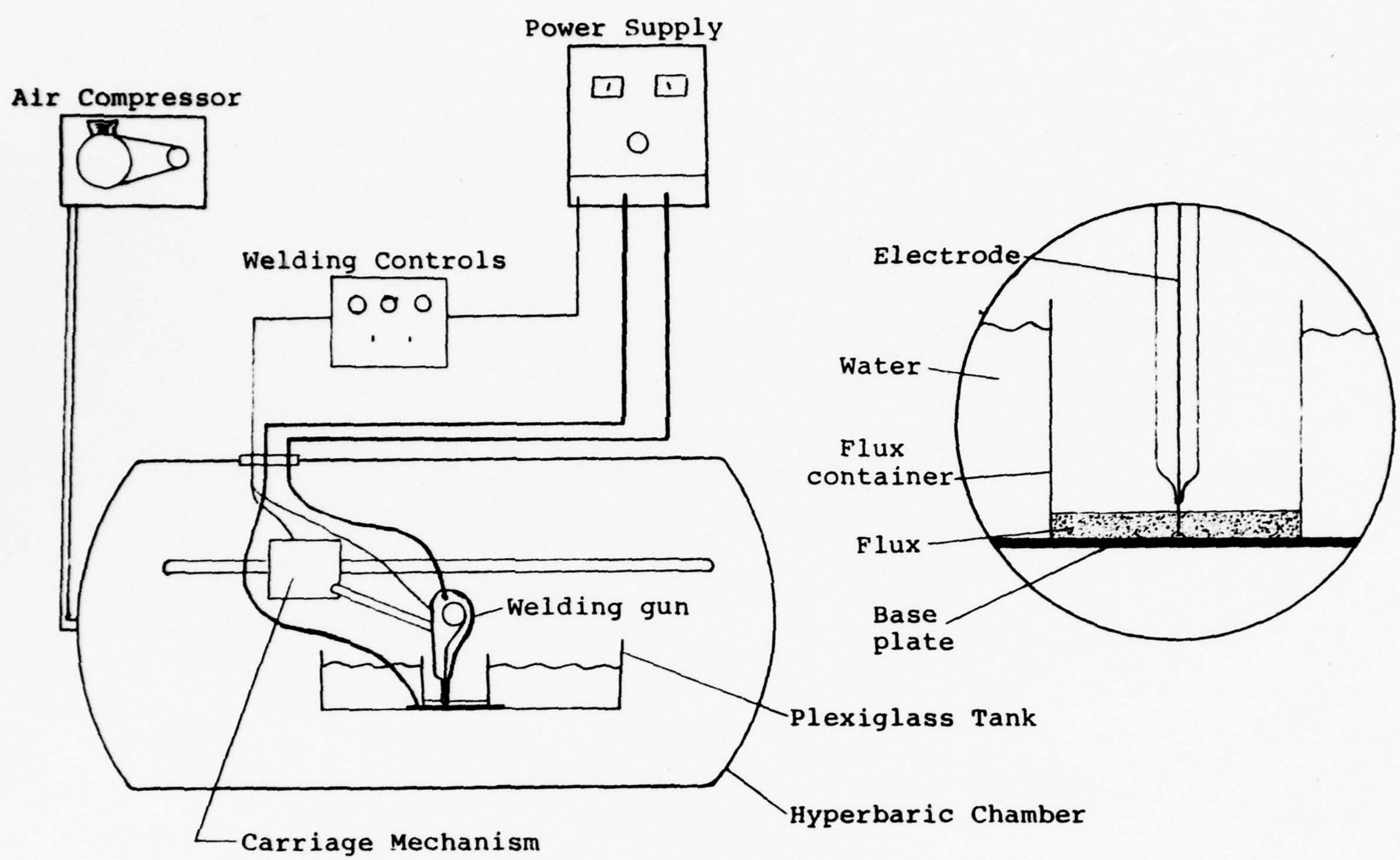


Figure 4.1 Schematic Diagram of Experimental Apparatus.

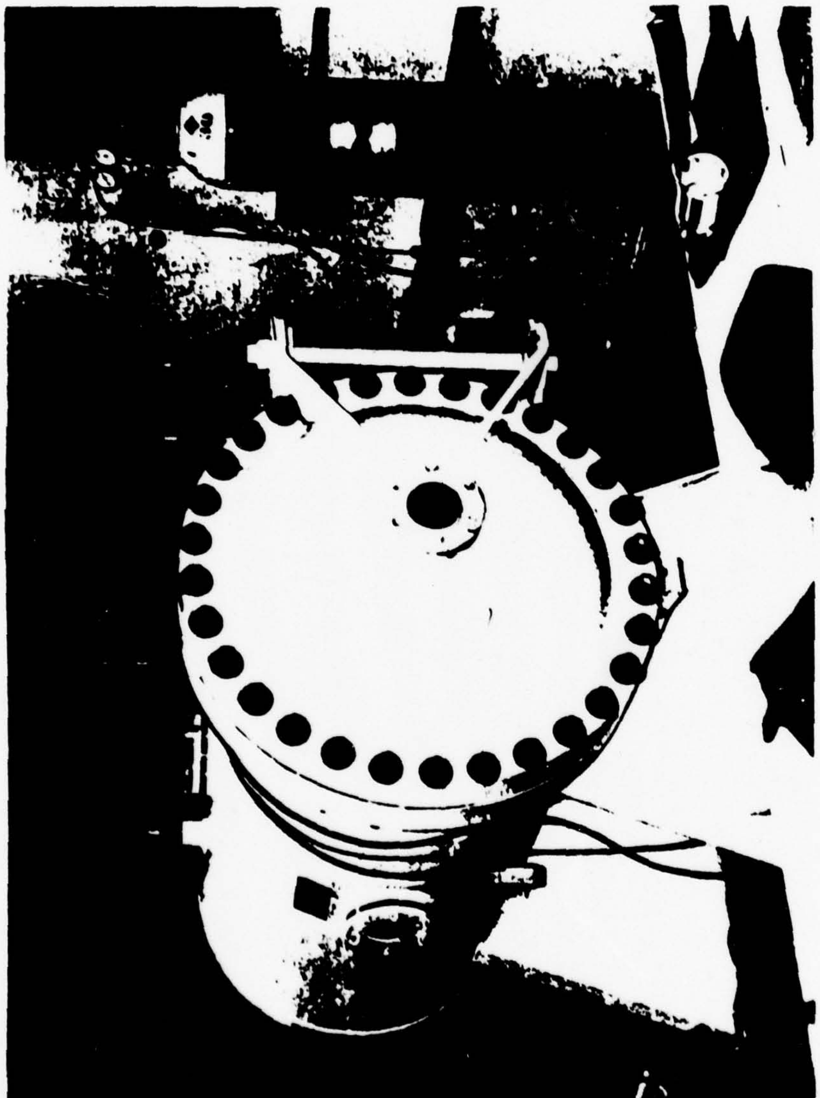


Photo 4.1 Hyperbaric Chamber

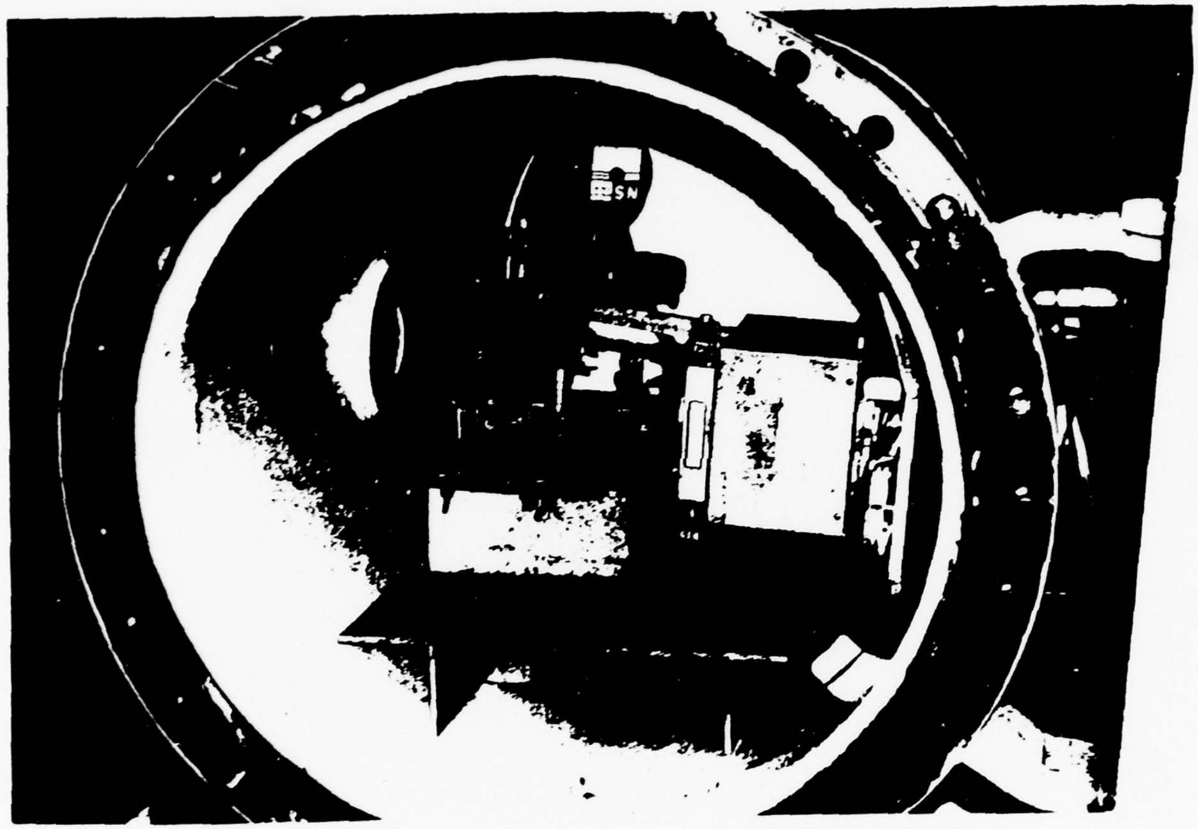


Photo 4.2 Welding Gun and Carriage Mechanism

travel speed and wire feed to be adjusted during welding if necessary. An AIRCOMATIC Model CV-450 welding machine was used as the welding power supply. This machine is a multipurpose constant potential machine with a maximum output capacity of 450 amperes.

To simulate a flux cartridge for the experimental investigation a container was constructed which could be attached to a plate by the use of small studs. The container served to hold the flux in position and to isolate the flux from the surrounding water during welding. The top of the container was open to the pressurized air atmosphere to enable the welding electrode to traverse along the plate. The schematic configuration of the flux container is illustrated in the insert in Figure 4.1, The flux container attached to a plate is shown in Photo 4.3. The interior dimension of the container are 2 inches by 8 1/2 inches.

Bead on plate welds were made on 1/4 inch cold rolled mild steel plates. The plated were 6 inches wide by 10 inches long with the welds being made longitudinally along the centerline. Mild steel welding wire of 0.030 inch diameter was used for all welds made. The wire feed was set at 12.5 feet/minute for all welds. Travel speed was set at 9 inches/ minute. The weld beads varied in length from 6 to 7 inches. The weld area was protected by a 3/4 inch layer of Lincoln

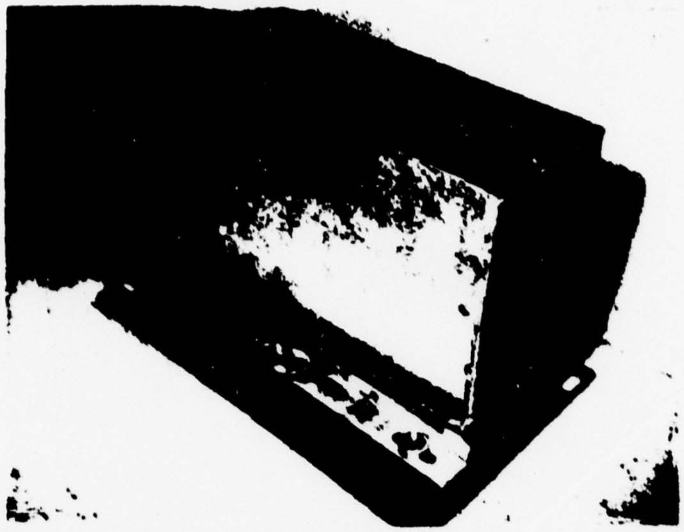


Photo 4.3 Flux container attached to plate.

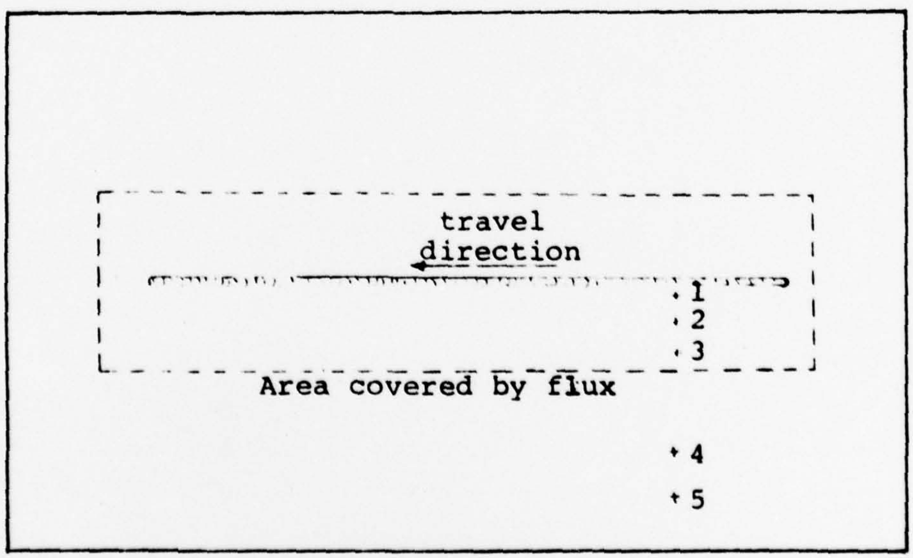


Figure 4.2 Thermcouple location on Welding Plate
(one-half actual size).

Flux No. 710 held by the flux container.

Welds were performed underwater in tap water at 0, 50, 100, 150, 200, 250, and 300 psig pressures. The welds were performed using reverse polarity. The potential setting of the power supply was increased slightly with increasing pressure to obtain welds which are similar in appearance and quality for the various pressures. Arc voltage and current were continuously recorded during welding by use of a Gould Brush 220 two channel stripchart recorder and a 500 Amp-50 millivolt shunt. Five Chromel-Alumel Type K thermocouples were attached to the surface of each steel plate as shown in Figure 4.2 in order to continuously monitor the temperatures during welding. The distances from the weld beads varied slightly from weld to weld due to slight differences in alignment of electrode from weld to weld.

An additional weld was performed at 0 psig with flux which was damp. This weld was performed in order to demonstrate one of the limitations of the method which will be discussed in Section 4.4.

After all welds were performed specimens of the welds were cut from the plates and mounted for polishing. The specimens were polished to 0.3 micro Alumina and then etched with 1% Nital. The welds were then photographed at X 10 and X 128 power magnification. Hardness readings were taken across the weld metal, heat affected zone (HAZ)

and base metal in knoop microhardness using a 100 gram weight.

4.3 COMPUTER HEAT FLOW ANALYSIS

A semi-empirical computer analysis has been formulated by Tsai[18] to analyze the heat flow in underwater welding in order to predict the cooling rates. Knowledge of the cooling rates for the weld metal and HAZ allows prediction of the metallurgical structure. Three experimentally determined weld parameters; bead width, penetration and ripple length are used to simulate a three-dimensional molten pool which is used as the inner boundry condition in the analysis. Heat flow in the base plate is then analyzed by finite element techniques. The mode of heat transfer to the water surrounding the weld region can be varied in the analysis to simulate different welding methods. For the analysis performed for comparison with the experimental data collected for the fluxshielded method a perfectly insulated layer of flux 2 1/2 inches in width was assumed to cover the plate along the centerline of the weld. Heat transfer to the water was assumed to be natural convection from a horizontal plate.

Inputs to the analysis were measured from the welds performed or were assumed to be reasonable values based on historical data. Arc voltage, arc current, initial

temperature, travel speed, bead width and bead penetration were all measured unputs. An arc efficiency of 60% was selected as a resonable efficiency for flux-shielded welding. Ripple length was assumed to be 0.8 centimeters for the analysis because measurement proved difficult. The heat input circle radius was assumed to be 0.7 centimeters.

Outputs of the analysis were cooling rates in the heat affected zone from 800°C. to 500°C. and temperature profiles for the thermocouple locations. A comparison of the results obtained with the experimental data is presented in the following section.

4.4 EXPERIMENTAL RESULTS AND DISCUSSION

A summary of the welding parameters and experimental results of the underwater flux-shielded welds performed is presented in Table 4.1. The bead widths, bead penetration and the ratio varied considerably for the various welds. The penetration tended to increase and the ratio of bead width to penetration tended to decrease as the arc power increased. A more detailed study with several welds of different power at each pressure would be needed to determine the exact effect the welding power and effect if any the pressure have on the welding bead shape.

Figure 4.3 is the voltage and current traces for the welding arc at 300 psig. Very similar traces were produced

Pressure [psig]	Equivalent Water Depth [ft]	Arc Voltage [volts]	Arc Current [amps]	Arc Power $[\frac{joule}{sec}]$	Bead Width [cm]	Bead Penetration [cm]	$\frac{\text{Bead Width}}{\text{Bead Penetration}}$
0	0	32	110	3520	0.655	0.135	4.85
50	113	26	140	3640	0.800	0.140	5.71
100	226	29	130	3770	0.685	0.150	4.57
150	340	31	170	5270	0.810	0.250	3.24
200	453	30	140	4200	0.735	0.090	8.17
250	567	31	160	4960	0.895	0.200	4.48
300	680	30	170	5100	0.880	0.225	3.91
0 Damp Flux	0	32	110	3520	0.680	0.100	6.80

Table 4.1 Summary of Welding Parameters and Results for Experimental Underwater Flux-Shielded Welds.

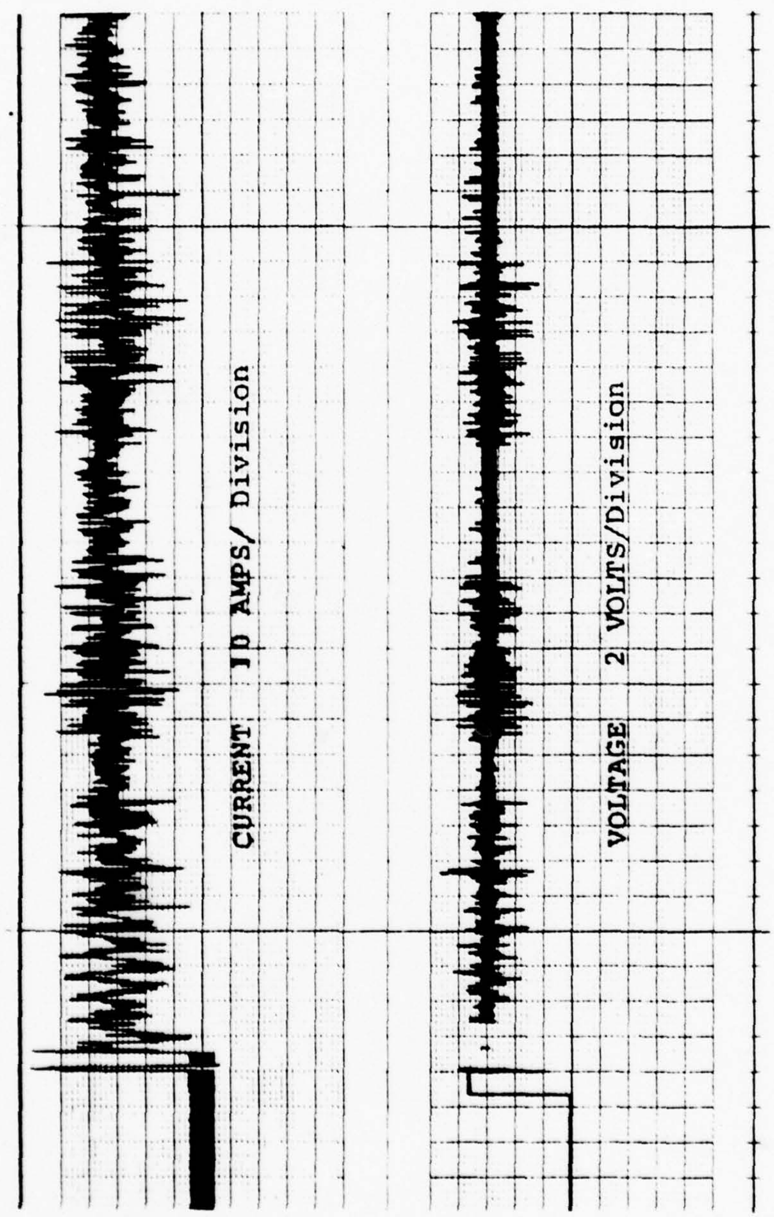


Figure 4.3 Voltage and Current Traces for Underwater Flux-Shielded Weld (300 psig).

for the other welds performed. A steady arc could be produced and maintained during welding regardless of the pressure. The arc power fcr the weld performed at 150 psig was higher than expected for no apparent reason.

The experimental data for the flux-shielded welds (dry flux) performed at 0 and 300 psig are presented in this section as examples. The data for the welds performed at the other pressures is presented in Appendix A. Photos 4.4 and 4.6 show the weld bead as it appears on the plate at 0 and 300 psig respectfully. All the welds performed were similar in external appearance regardless of the pressure Photos 4.5 and 4.7 are micro and macro structures of the welds at 0 and 300 psig respectfully. None of the welds performed contained slag inclusions, porosity or cracks. Figures 4.4 and4.6 are the microhardness readings combined with the microstructure photographs indicate that no martensite was present in the weld metal or heat affected zone for any of the welds performed. The microhardness readings in the weld metal were higher than expected. This may be due to impurities and trace elements from the flux. Fluxes of different composition could be experimented with, in an attempt to alleviate this problem.

The computer analysis predicted cooling rates of 3.2 to 4.0 seconds from 800°C. to 500°C. in the heat affected zones of the welds performed. Examination of these times

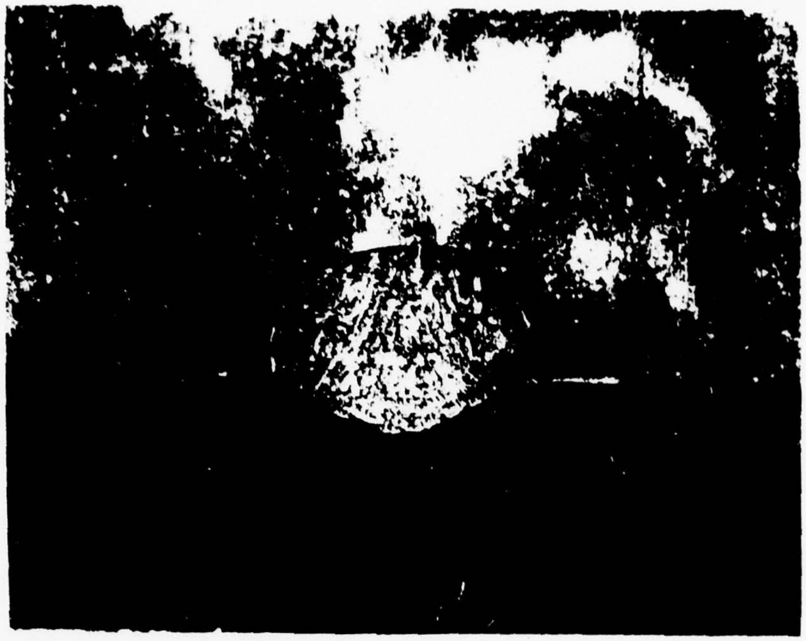
with respect to Figure 2.1 indicates that the microstructure of the flux-shielded welds should be similar to that of air welds. Based on these predicted cooling rates no martensite should appear in the heat affected zone which was observed experimentally to be the case. Figures 4.5 and 4.7 illustrate the temperature profiles calculated by the computer analysis and the temperatures measured by the computer analysis for the welds at 0 and 300 psig respectfully. Table 4.2 is a summary of the thermocouple locations for all the welds performed. The measured heating and cooling rates were slower than predicted by the computer analysis. The temper-ture difference between the predicted and measured tended to increase as the pressure increased. This indicated that the pressure either has an effect on the heat transfer rates or the pressure effects one or more of the welding parameters such as ripple length or radius of heat input circle which are inputs to the computer analysis. A detailed study and examination of the computer analysis would be needed to account for the differences in cooling rates and temperatures. Although the computer analysis differs from the experimental data, the temperatures and times are of the same order indi-cating that the computer analysis is reasonably valid for prediction the cooling rates in the heat affected zone.

All the welds discussed above were for the flux-shield-ed method with dry flux. One weld was performed at 0 psig

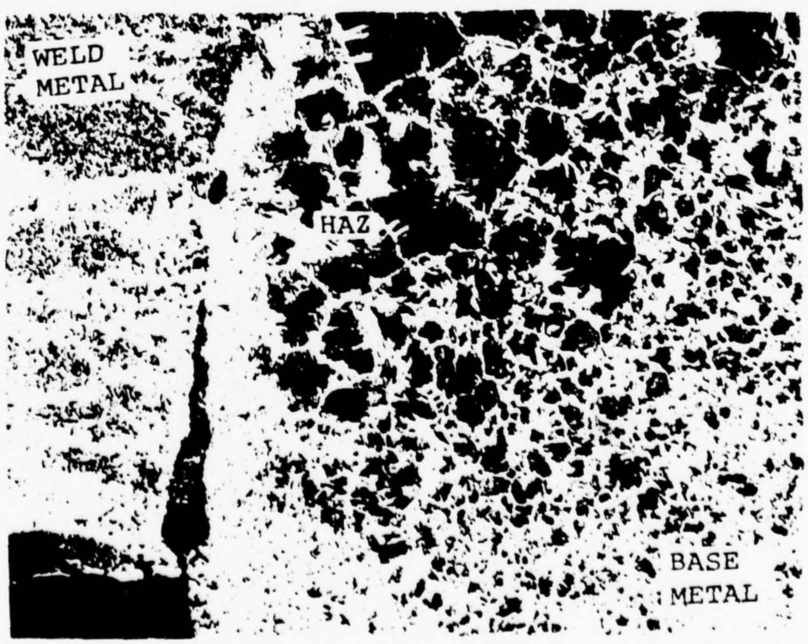
Pressure [psig]	Thermocouple locations from weld centerline #1 / #2 / #3 [cm]
0	0.79 / 1.11 / 1.75
50	0.64 / 0.95 / 1.59
100	0.64 / 0.95 / 1.59
150	0.95 / 1.27 / 1.91
200	0.95 / 1.27 / 1.91
250	0.95 / 1.27 / 1.91
300	0.79 / 1.11 / 1.75

Table 4.2 Thermocouple locations on test plates.

Photo 4.4 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (0 psig).



X 10



X 128

Photo 4.5 Micro and Macro Structures of Underwater Flux-Shielded (0 psig).

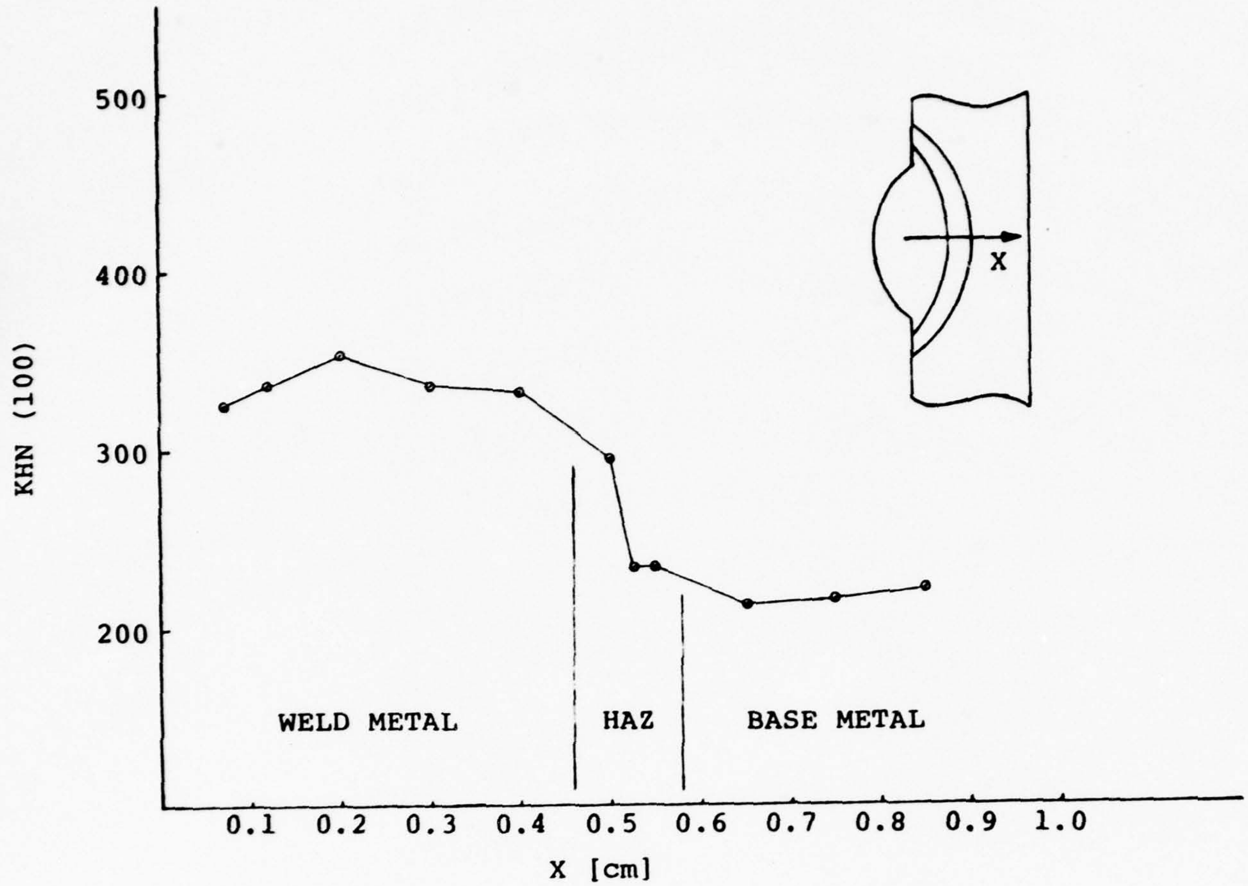


Figure 4.4 Microhardness Readings in Underwater Flux-Shielded Weld (0 psig).

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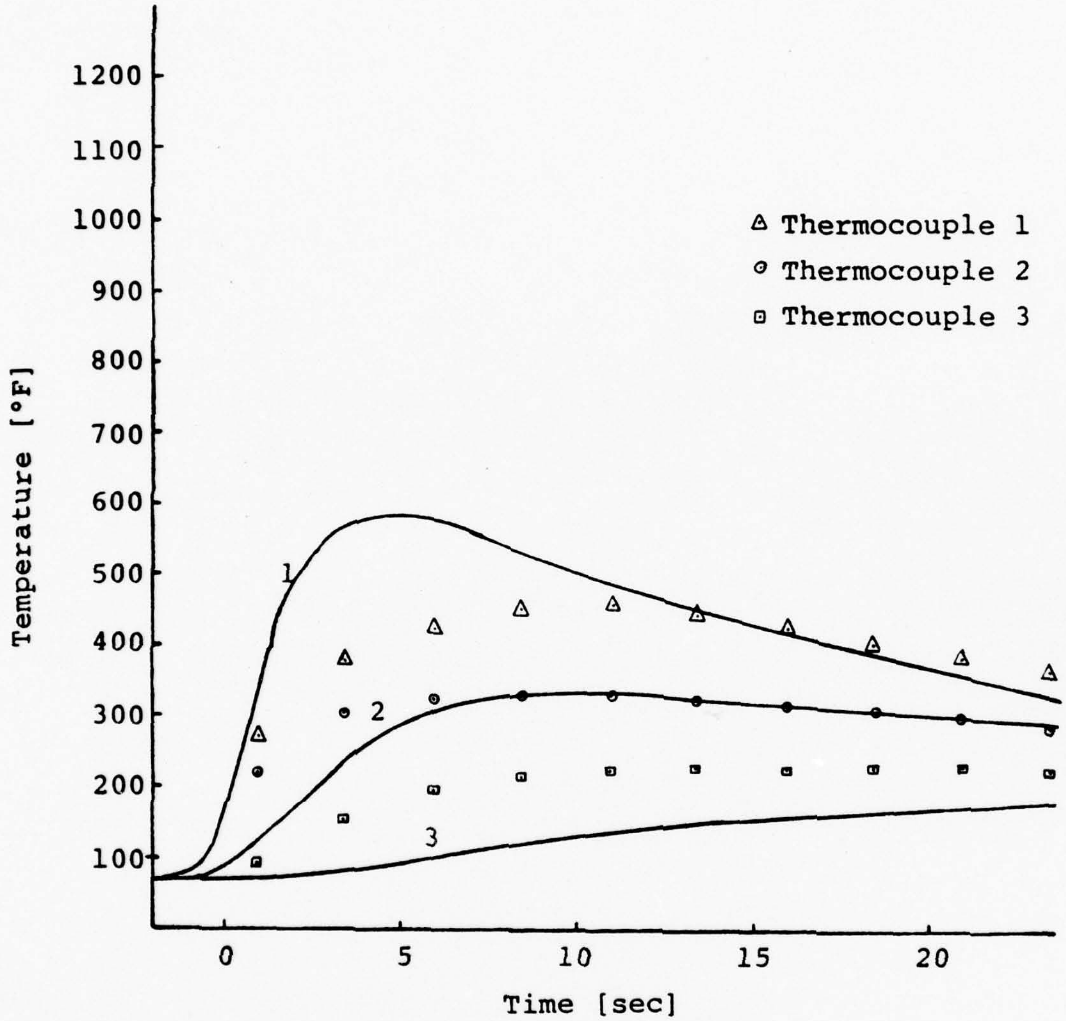

Figure 4.5 *Calculated Temperature and Measured* Temperature in Underwater Flux-Shielded Weld (0 psig).

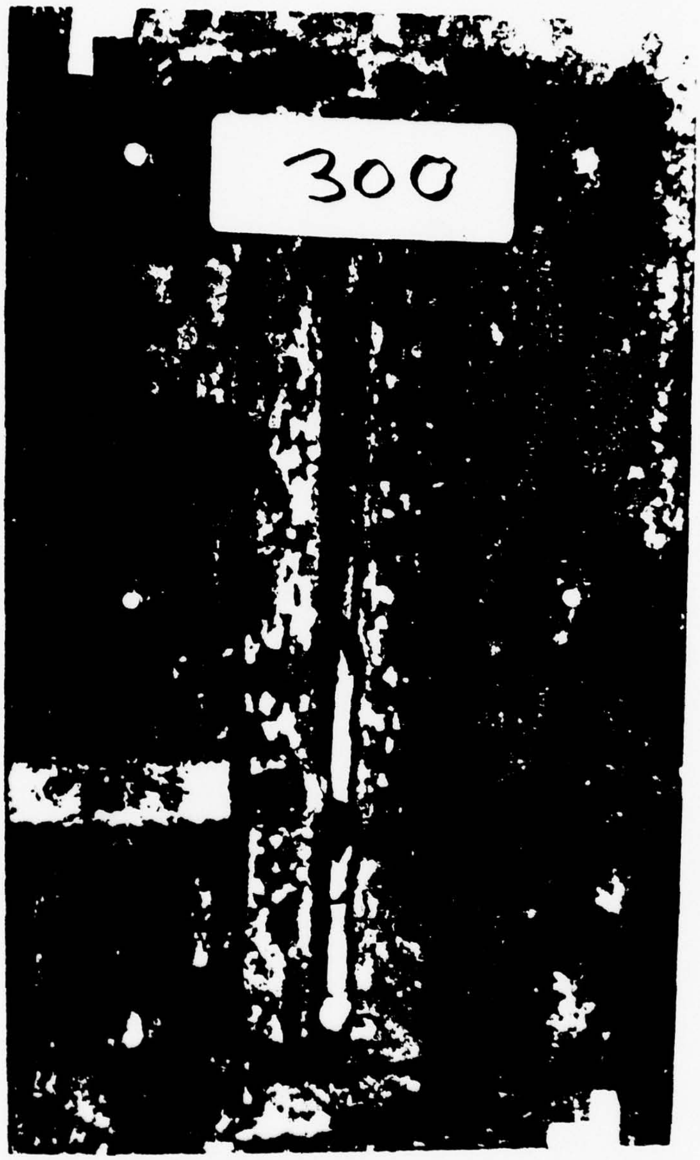

Photo 4.6 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (300 psig).

X 10

X 128

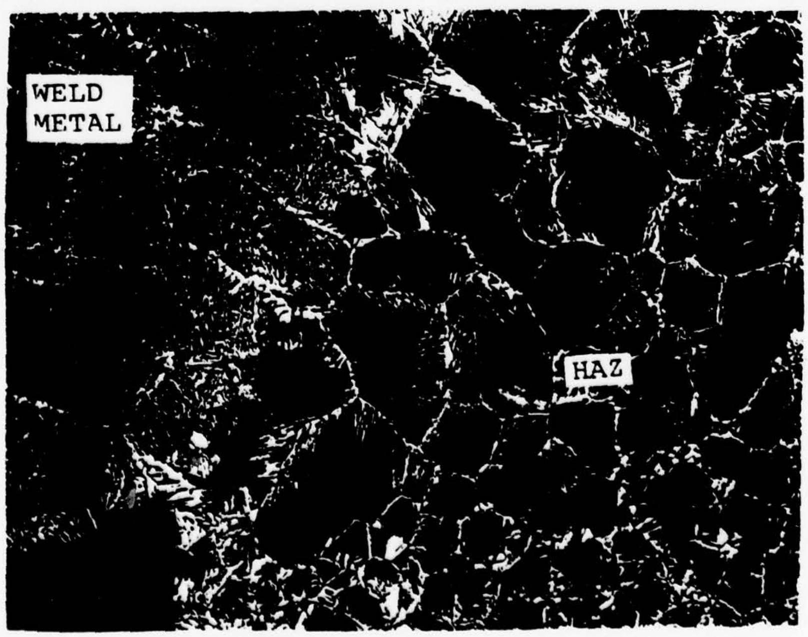

Photo 4.7 Micro and Macro Structures of Underwater Flux-Shielded (300 psig).

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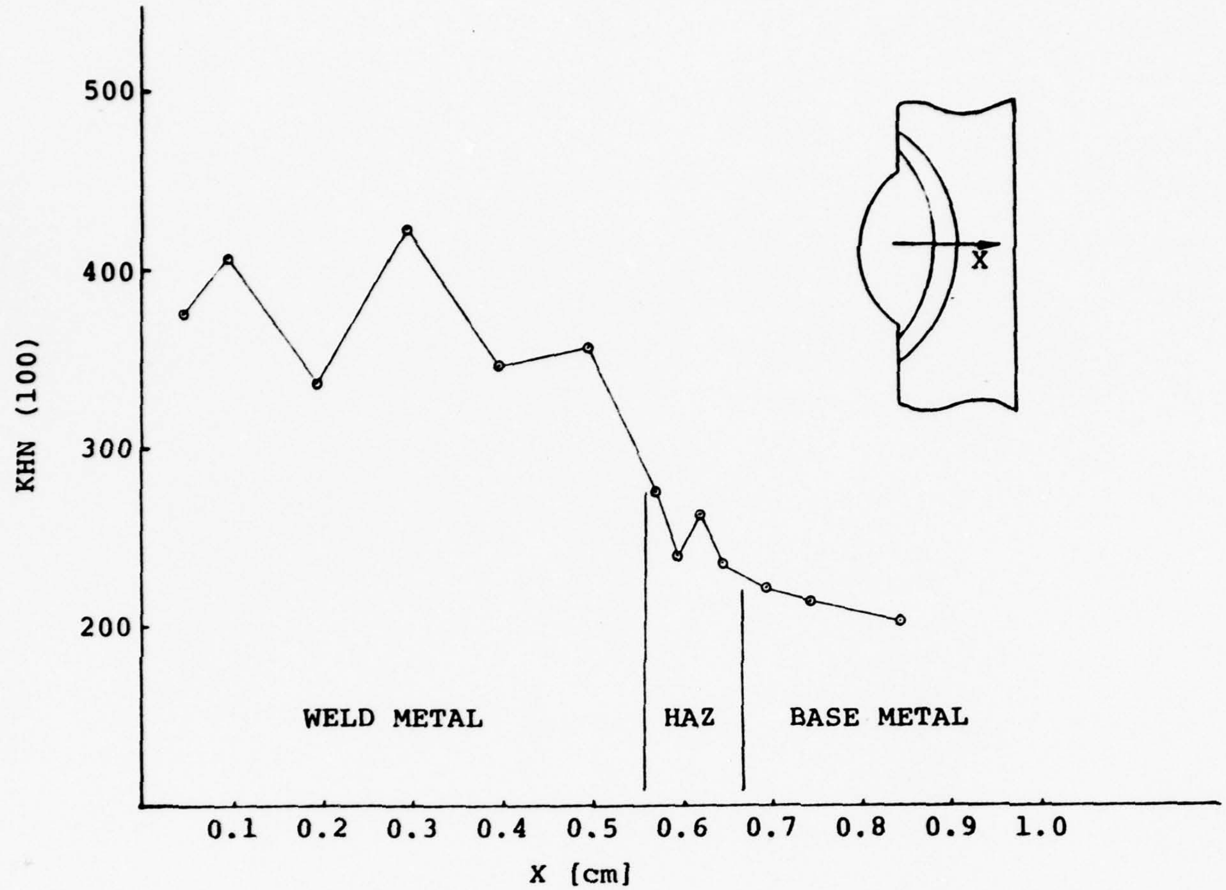


Figure 4.6 Microhardness Readings in Underwater Flux-Shielded Weld (300 psig).

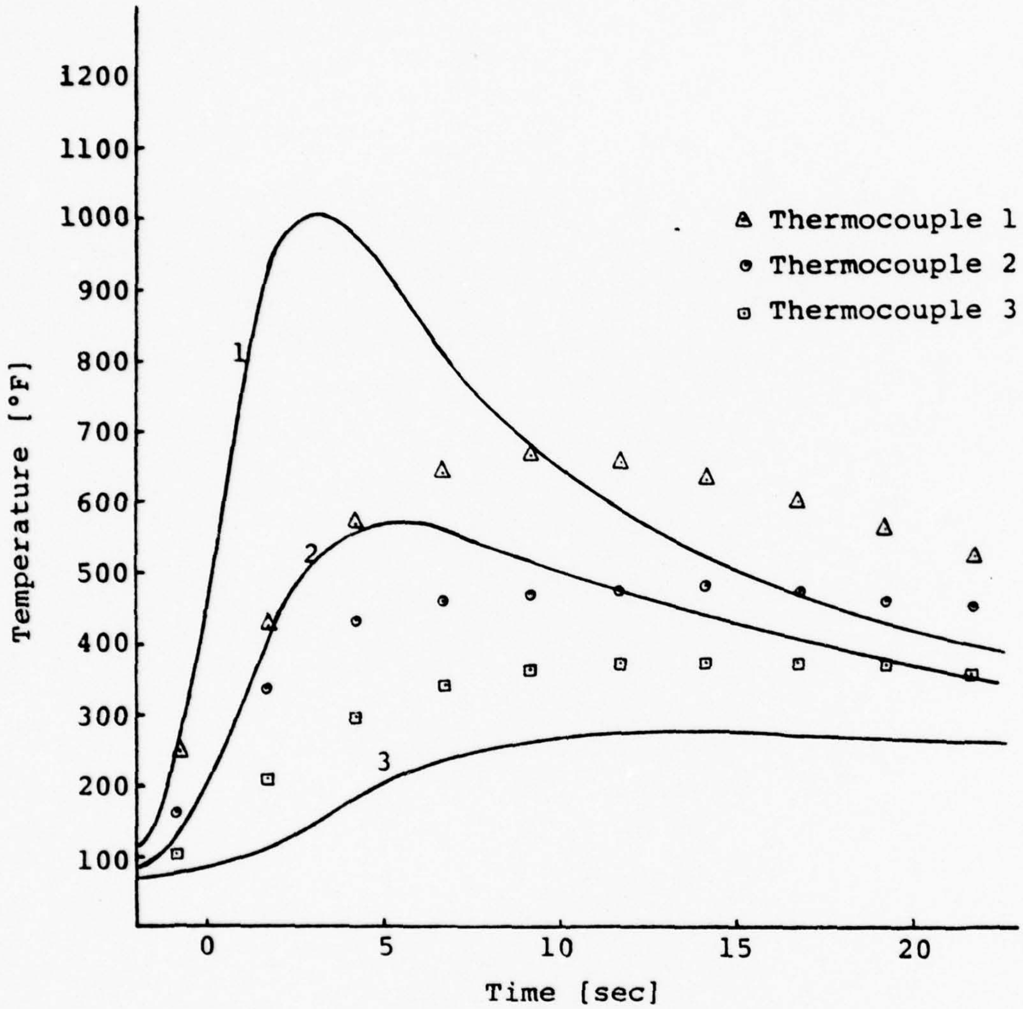
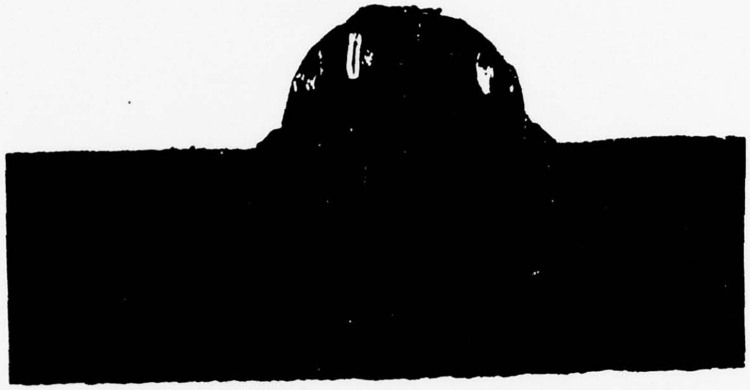


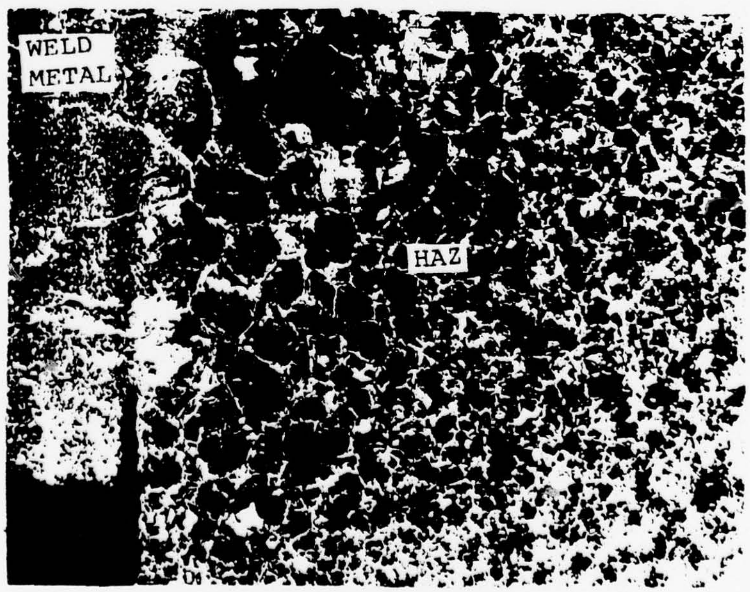
Figure 4.7 Calculated Temperature and Measured Temperature in Underwater Flux-Shielded Weld (300 psig).

with damp flux to illustrate a limitation of the method. Photo 4.8 are the micro and macro structures of this weld. Large slag inclusions and a good deal of porosity is present in the weld metal. No cracks were observed however. Figure 4.8 are the microhardness readings of the weld. The microhardness readings and the microstructure photo indicate no matensite in the heat affected zone. Higher hardness readings were observed in the weld metal for the damp flux weld than for any of the dry flux welds indicating that the presence of the moistrue may have affected the metallurgical structure of the weld metal. This weld performed with damp flux demonstrates that the weld must remain absolutely dry if good quality welds are to be obtained.

The experiments performed indicate that the flux-shielded method may be suitable for use in the deep sea. The quality of welds obtained was good when the flux was dry. The degradation of the weld quality when the flux is damp presents a design problem for the development of the method. Flux cartridges must be developed to insure the flux remains dry or a waterproof type flux must be developed. Pressures up to 300 psig (680 feet of water depth) did not affect the ability to perform the welds or degrade the weld quality.

X 10





X 128

Photo 4.8 Micro and Macro Structures of Underwater Flux-Shielded Weld with Damp Flux (0 psig).

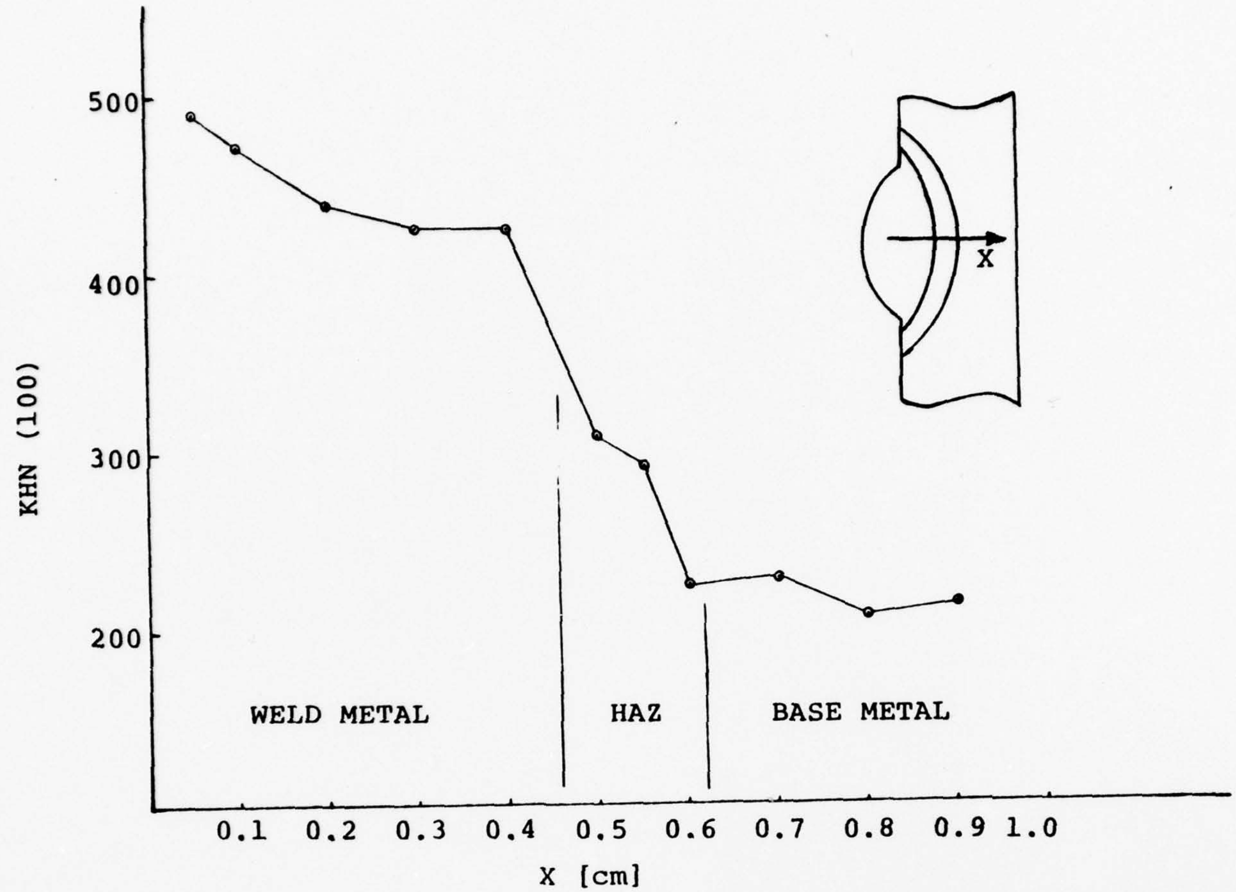


Figure 4.8 Microhardness Readings in Underwater Flux-Shielded Weld with Damp Flux (0 psig).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. In the near future man will significantly begin exploring the continental slopes of the oceans. Offshore structures located in these waters will require repair, modification and possibly construction at sea. No methods of underwater welding used commercially is suitable for the use in the deep sea (water depths greater than 1000 feet).
2. A review of underwater welding methods with respect to their applicability to deep sea use indicates:
   a) Man must be removed from direct contact with the underwater welding process.
   b) Welding systems must be automated and remotely controlled.
   c) Good quality welds can only be obtained in underwater welds when the water is removed from the weld area.
3. The experimental work performed indicates the underwater flux-shielded process may be suitable for deep sea use.
4. Good bead on plate welds were produced using the underwater flux-shielded method under experimental conditions at simulated depths up to 680 feet.

The welds produced were good in appearance, had good penetration, contained no martensite in the weld metal or HAZ, contained no porosity or slag inclusions, and showed no signs of hydrogen cracking.

5. Experimental work has proven that the flux used in the underwater flux-shielded method must remain dry prior to and during welding. The presence of moisture in the flux produces welds which contain slag inclusions, increased porosity and increased hardness.
6. Increases in pressure up to the maximum of 300 psig did not affect the ability to lay the bead, the weld appearance or the weld hardness. Slight increases in arc power with increased pressure were required to obtain similar weld beads.
7. The computer analysis predicted faster heating and cooling rates than were observed by thermocouple measurements.
8. The differences in temperatures between that predicted by the computer analysis and that measured by the thermocouples tended to increase as the pressure increased. This indicates that either the heat transfer or the pressure affects the welding parameters such as diameter of heat source, ripple length, etc. which are inputs to the

computer analysis.

5.2 RECOMMENDATIONS FOR FUTURE WORK

1. Continue development of the underwater flux-shielded method toward construction of a prototype unit able to perform welds under actual sea conditions. Particular emphasis on the development and testing of the flux cartridge is needed due to the requirement of dry flux to perform good quality welds.
2. Continue experimental work on the underwater flux-shielded method with other types of fluxes. Development of waterproof fluxes would simplify the design and result in a more rapid development of the method.
3. A detailed examination of the computer analysis and the welding parameters is needed to explain the discrepancies between the temperatures predicted and the temperatures measured. A collection and evaluation of more experimental data is required to examine the increased difference in temperatures between predicted and measured with increased pressure. If this phenomena is found to exist under different sets of conditions an examination of the cause could be undertaken.

Appendix A- Experimental Results

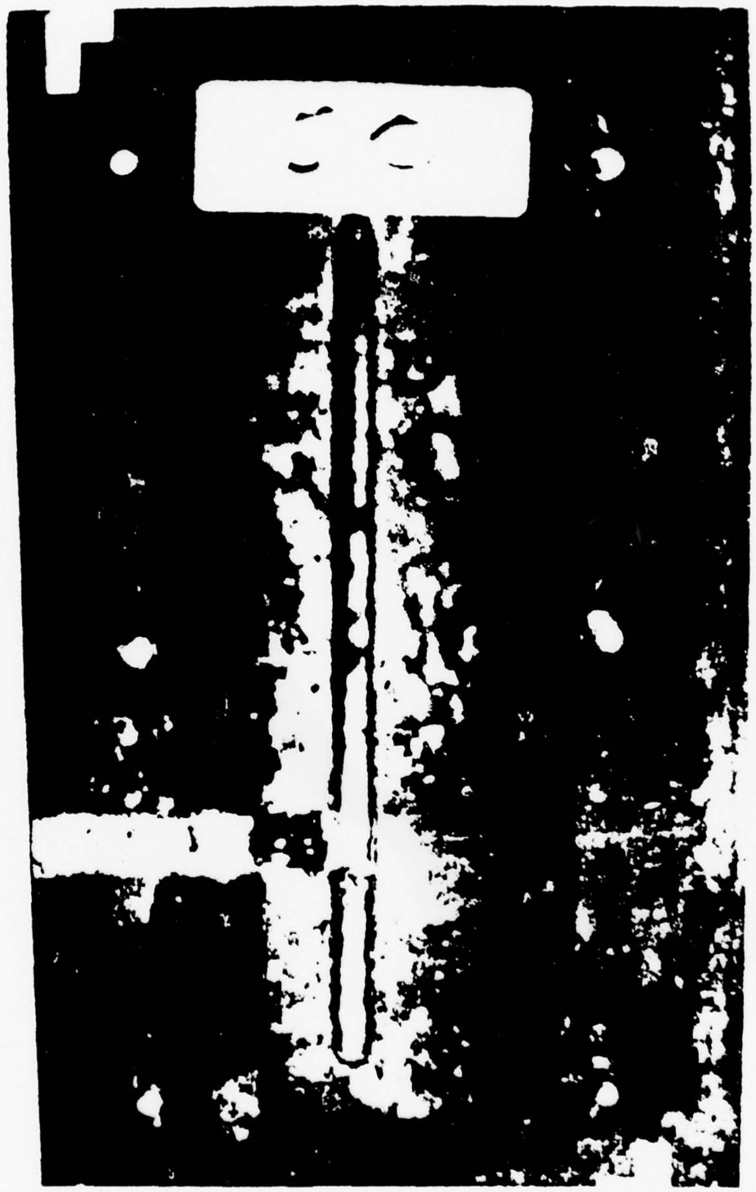
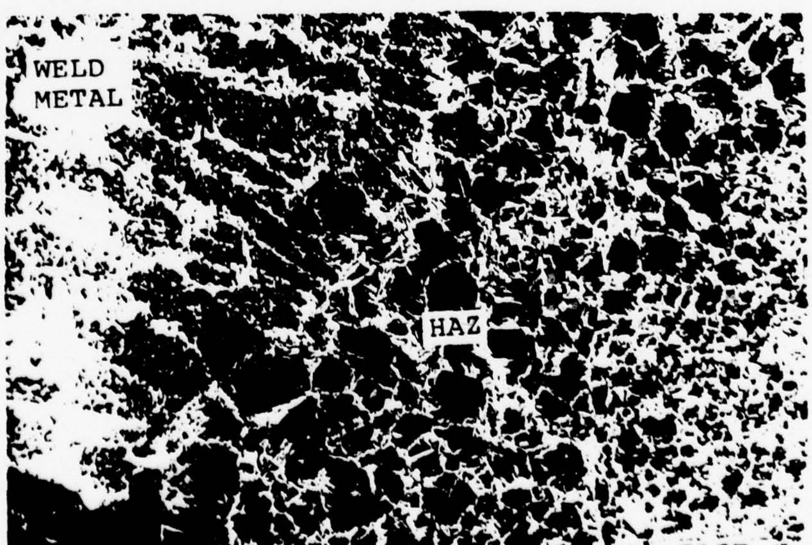


Photo A.1 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (50 psig).

X 10



X 128

Photo A.2 Micro and Macro Structures of Underwater Flux-Shielded (50 psig).

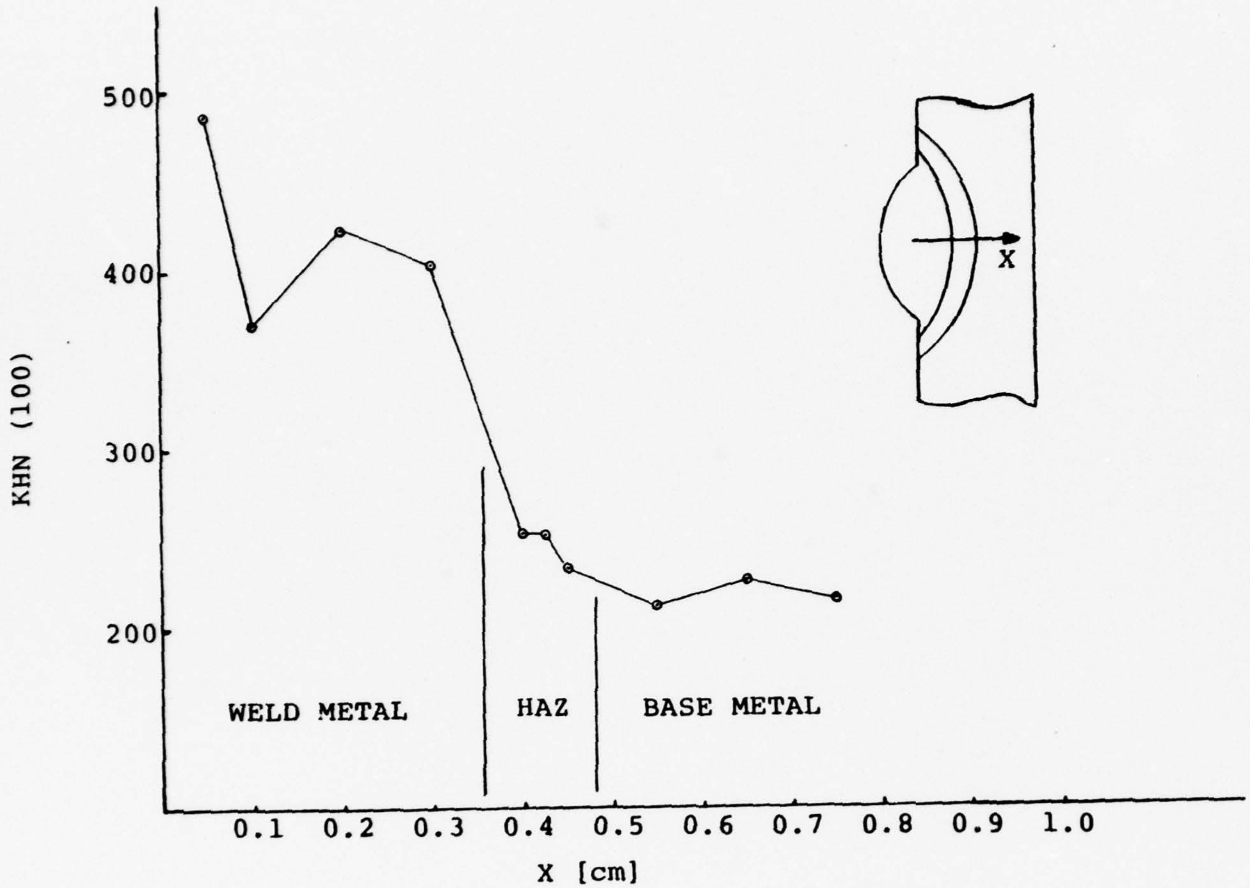


Figure A.1 Microhardness Readings in Underwater Flux Shielded Weld (50 psig).

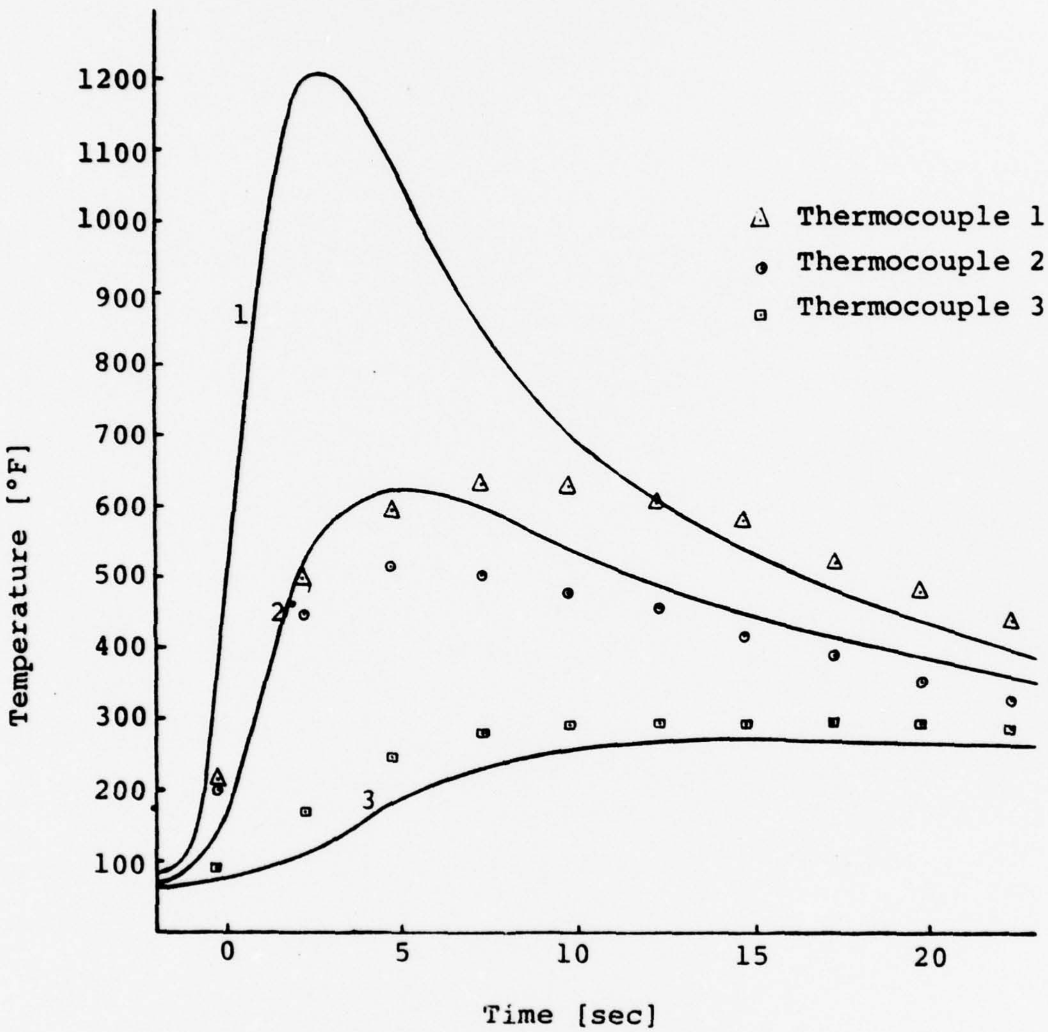


Figure A.2 Calculated Temperature and Measured Temperature in Underwater Flux Shielded Weld (50 psig).

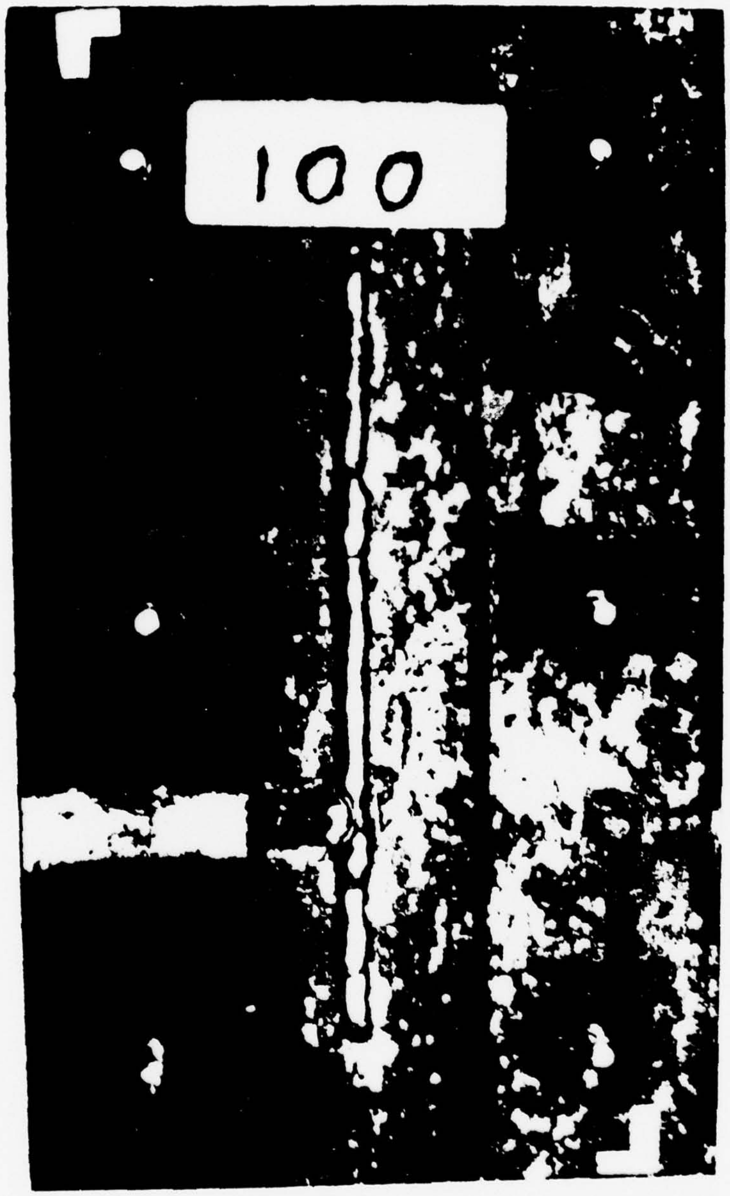
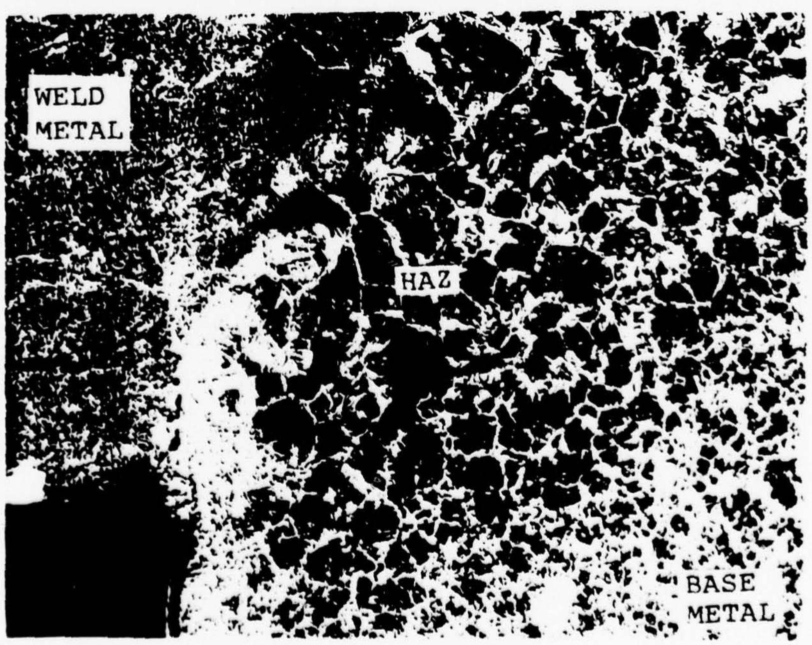


Photo A.3 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (100 psig).

X 10



X 128

Photo A.4 Micro and Macro Structures of Underwater Flux-Shielded (100 psig).

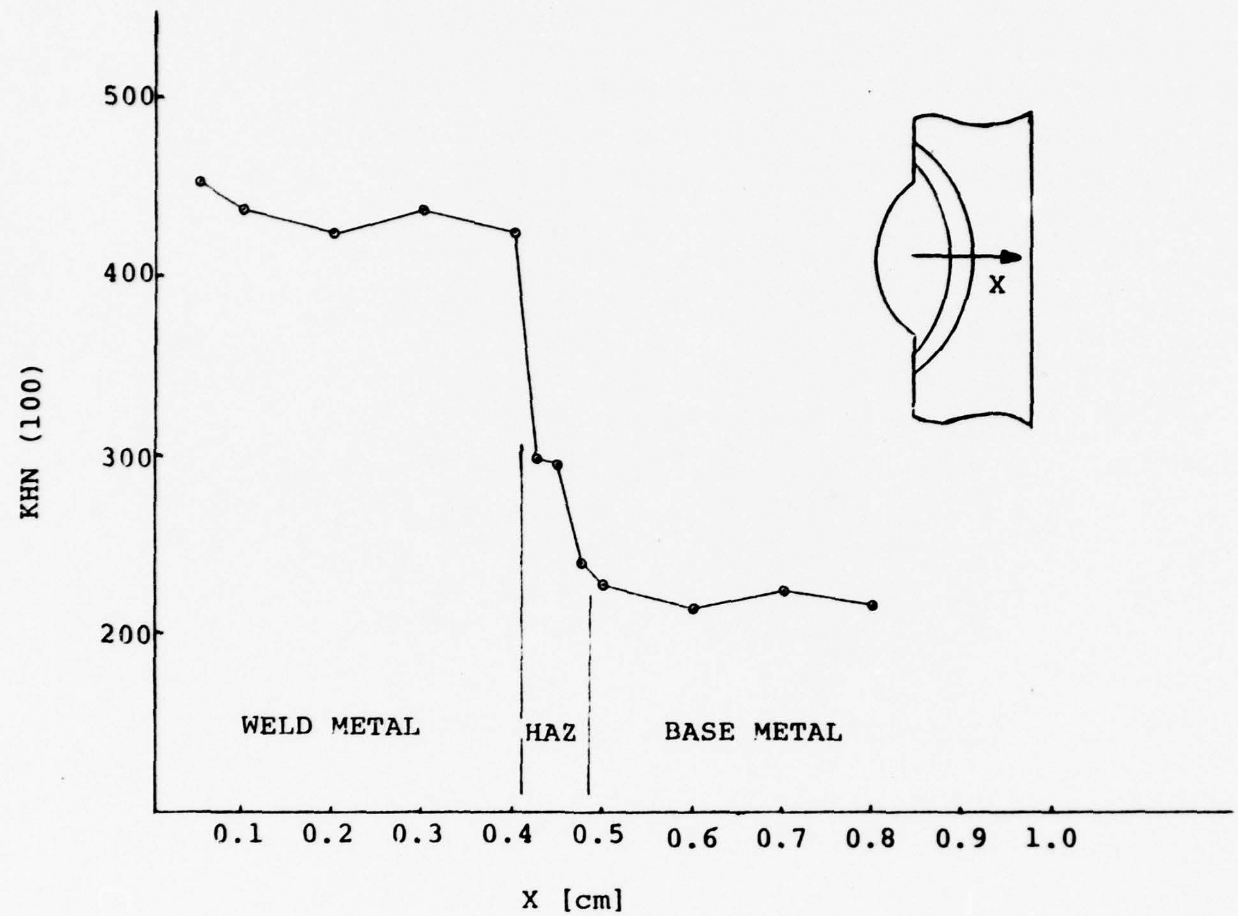


Figure A.3 Microhardness Readings in Underwater Flux-Shielded Weld (100 psig).

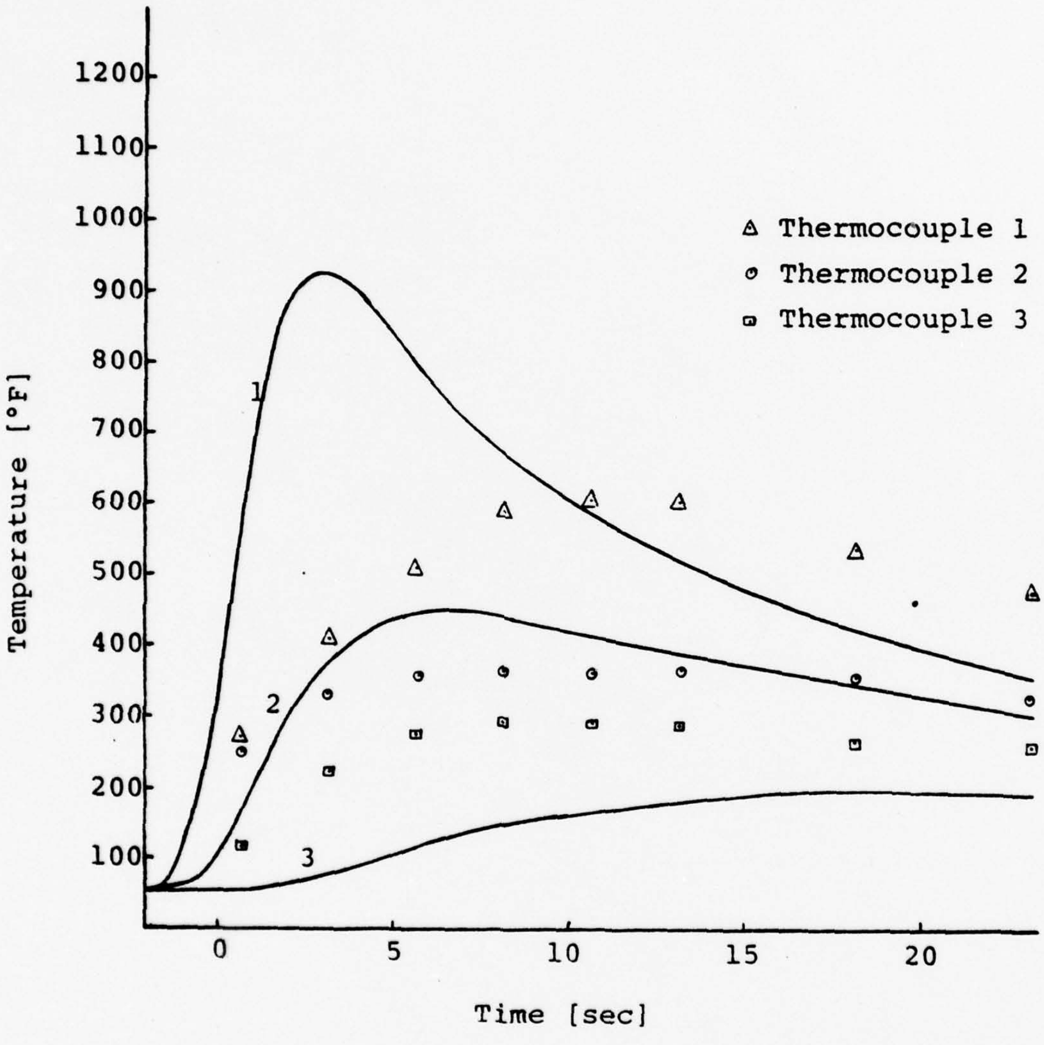
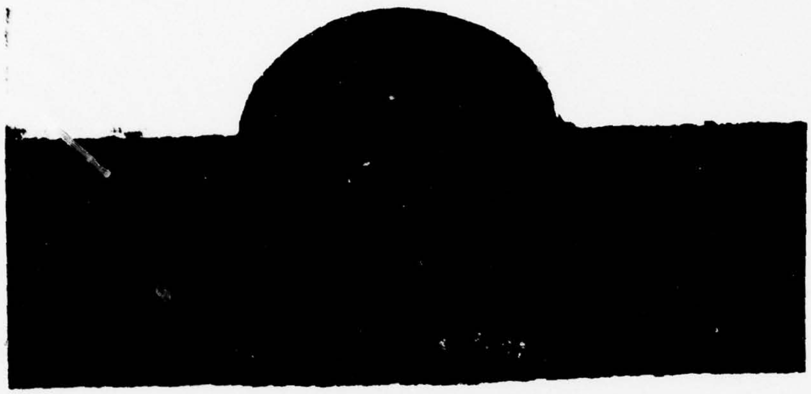


Figure A.4 Calculated Temperature and Measured Temperature in Underwater Flux-Shielded Weld (100 psig)

Photo A.5 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (150 psig).

X 10



X 128

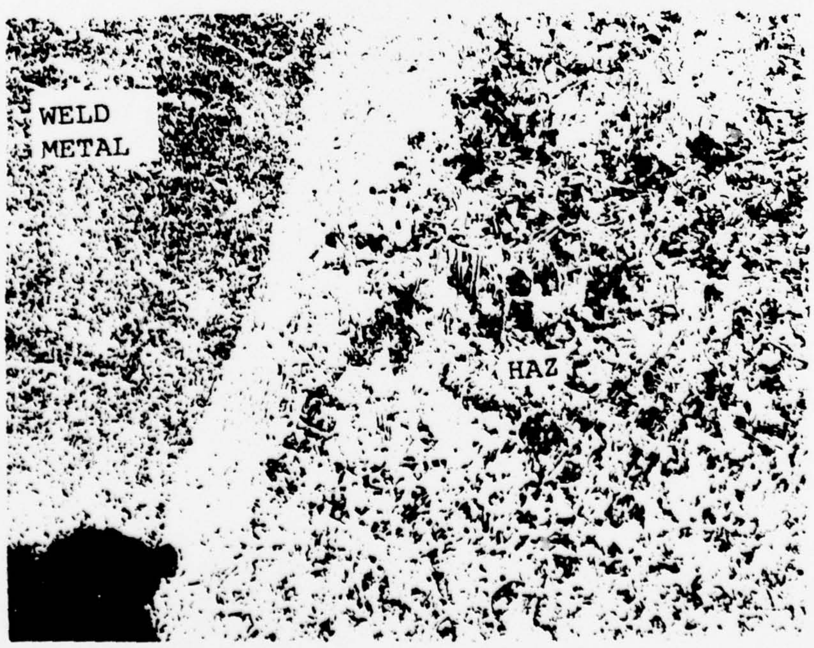


Photo A.6 Micro and Macro Structures of Underwater Flux-Shielded (150 psig).

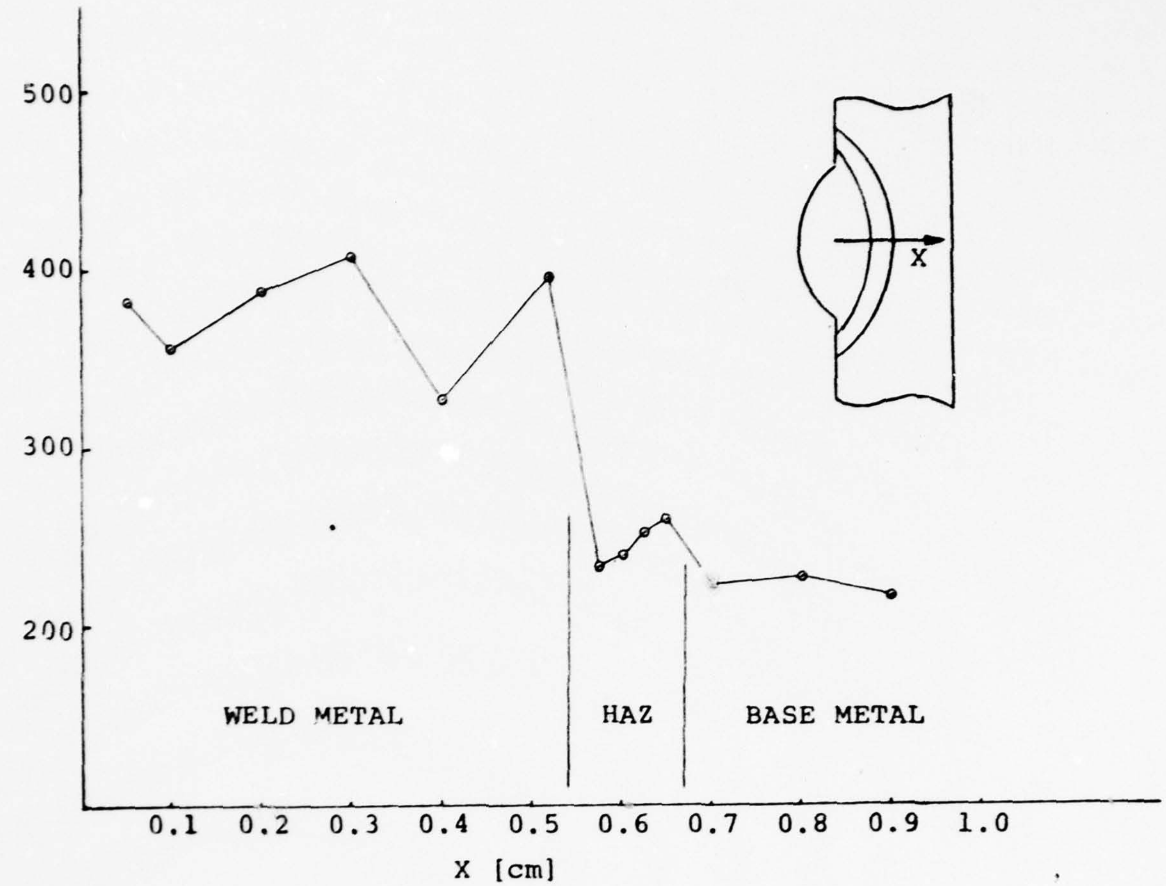


Figure A.5 Microhardness Readings in Underwater Flux-Shielded Weld (150 psig).

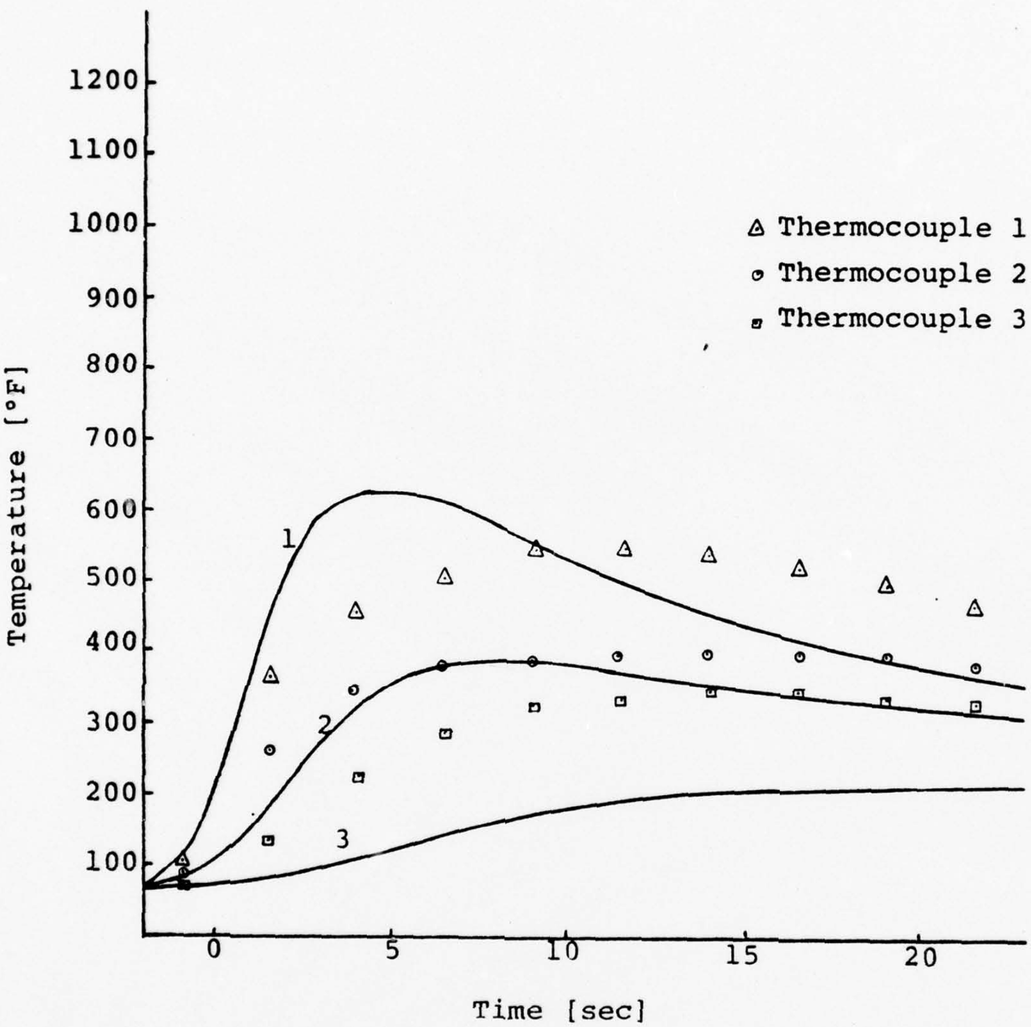


Figure A.6 Calculated Temperature and Measured Temperature in Underwater Flux-Shielded Weld (150 psig).

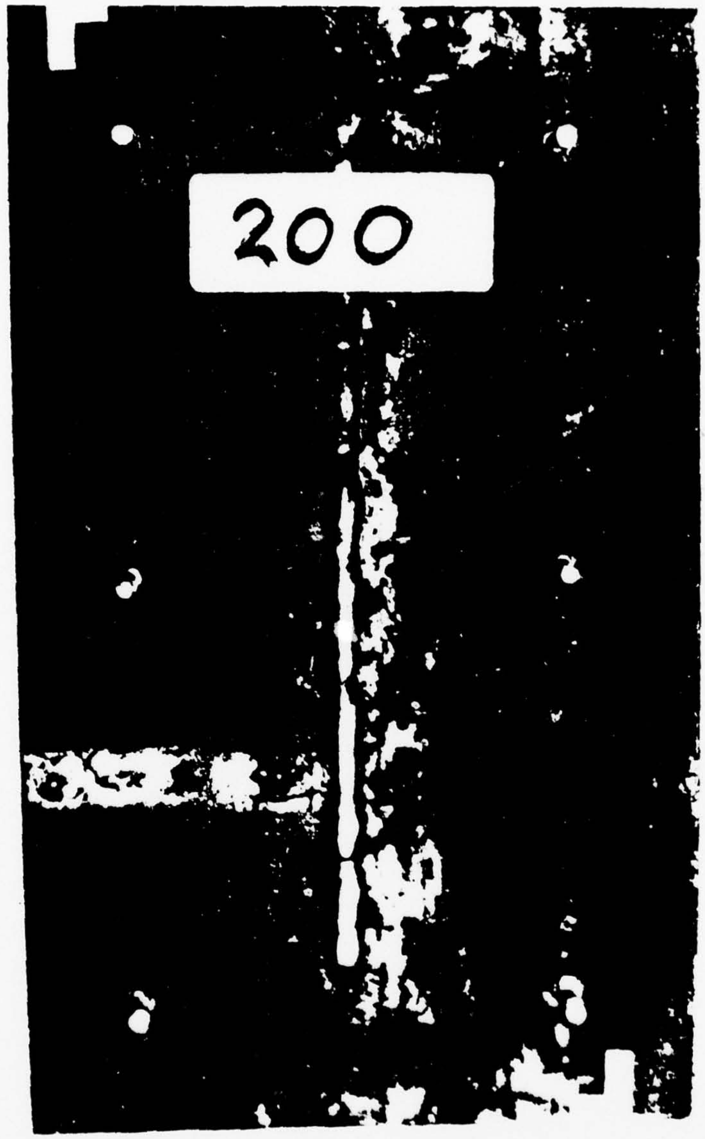


Photo A.7 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (200 psig).

X 10

X 128

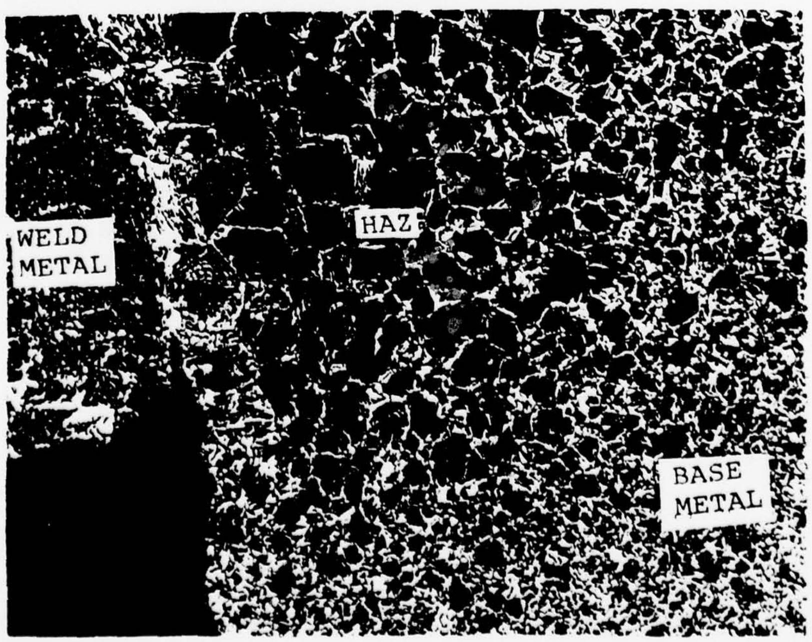


Photo A.8 Micro and Macro Structures of Underwater Flux-Shielded (200 psig).

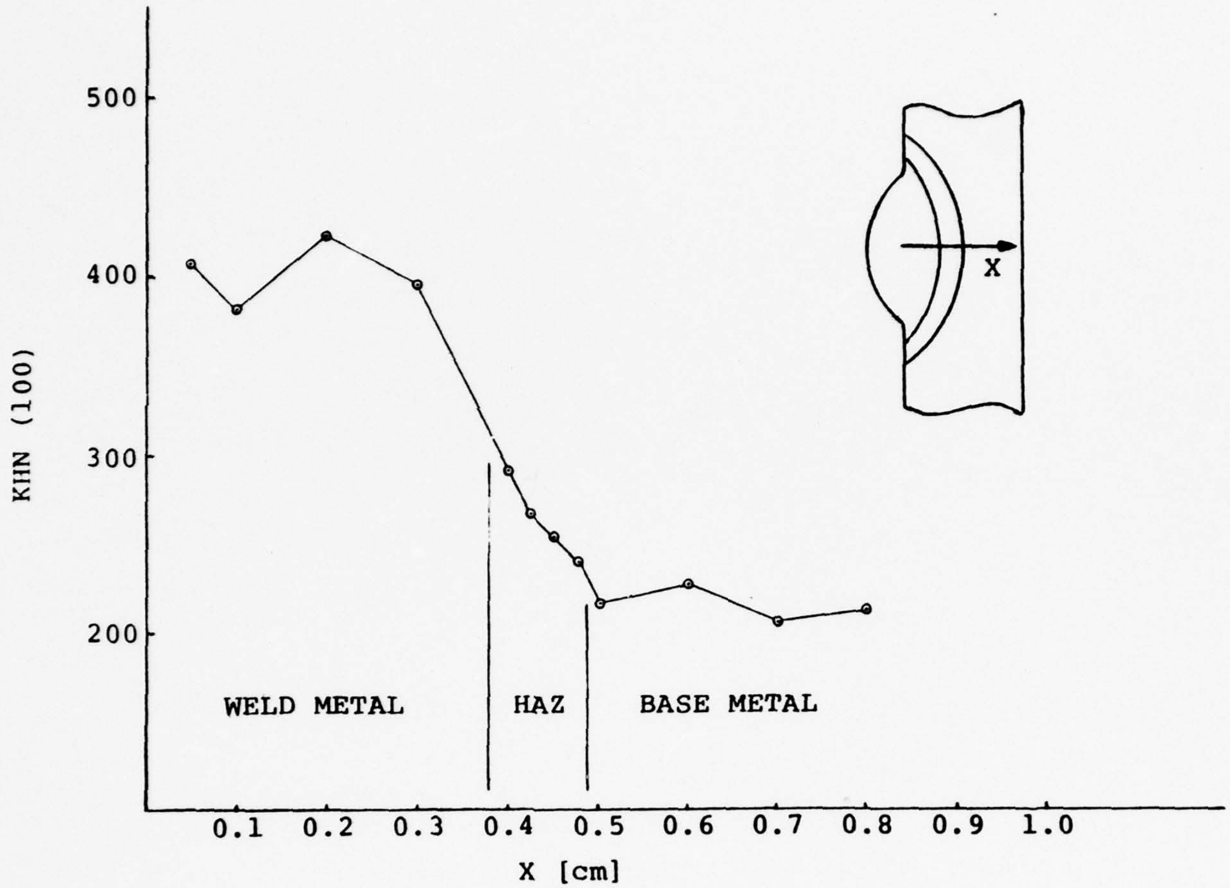


Figure A.7 Microhardness Readings in Underwater Flux-Shielded Weld (200 psig).

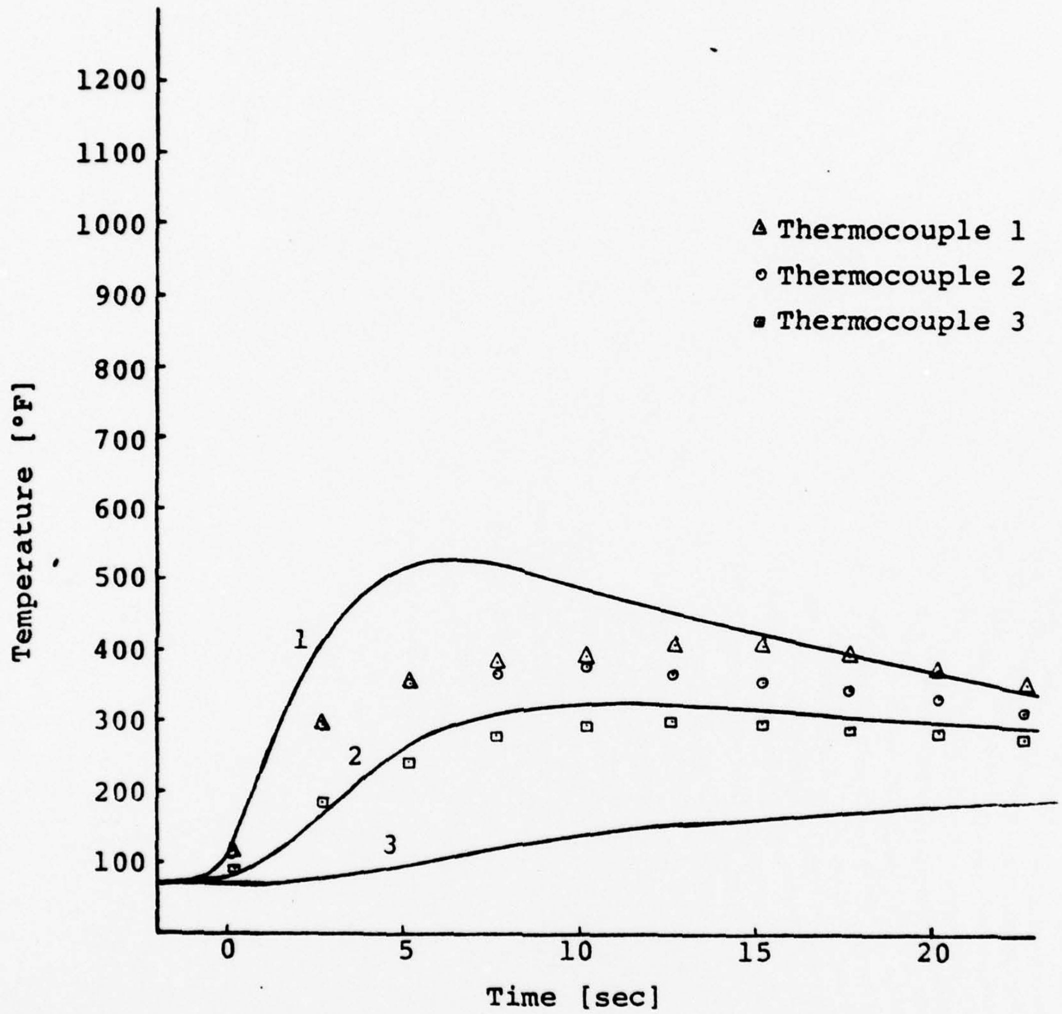


Figure A.8 Calculated Temperature and Measured Temperature in Underwater Flux-Shielded Weld (200 psig).

Photo A.9 Welding Bead on 1/4" Thick Plate in Underwater Flux-Shielded (250 psig).

X 10

X 128

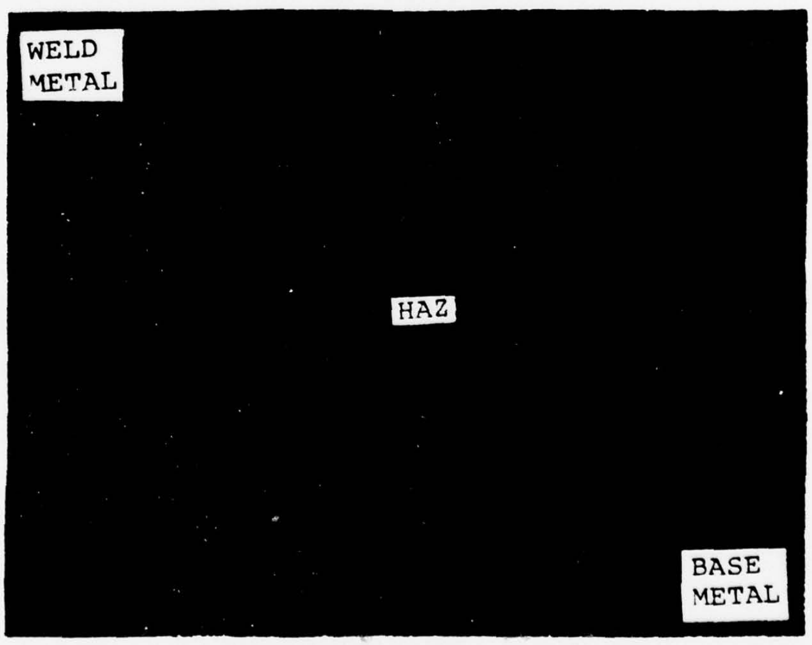


Photo A.10 Micro and Macro Structures of Underwater Flux-Shielded (250 psig).

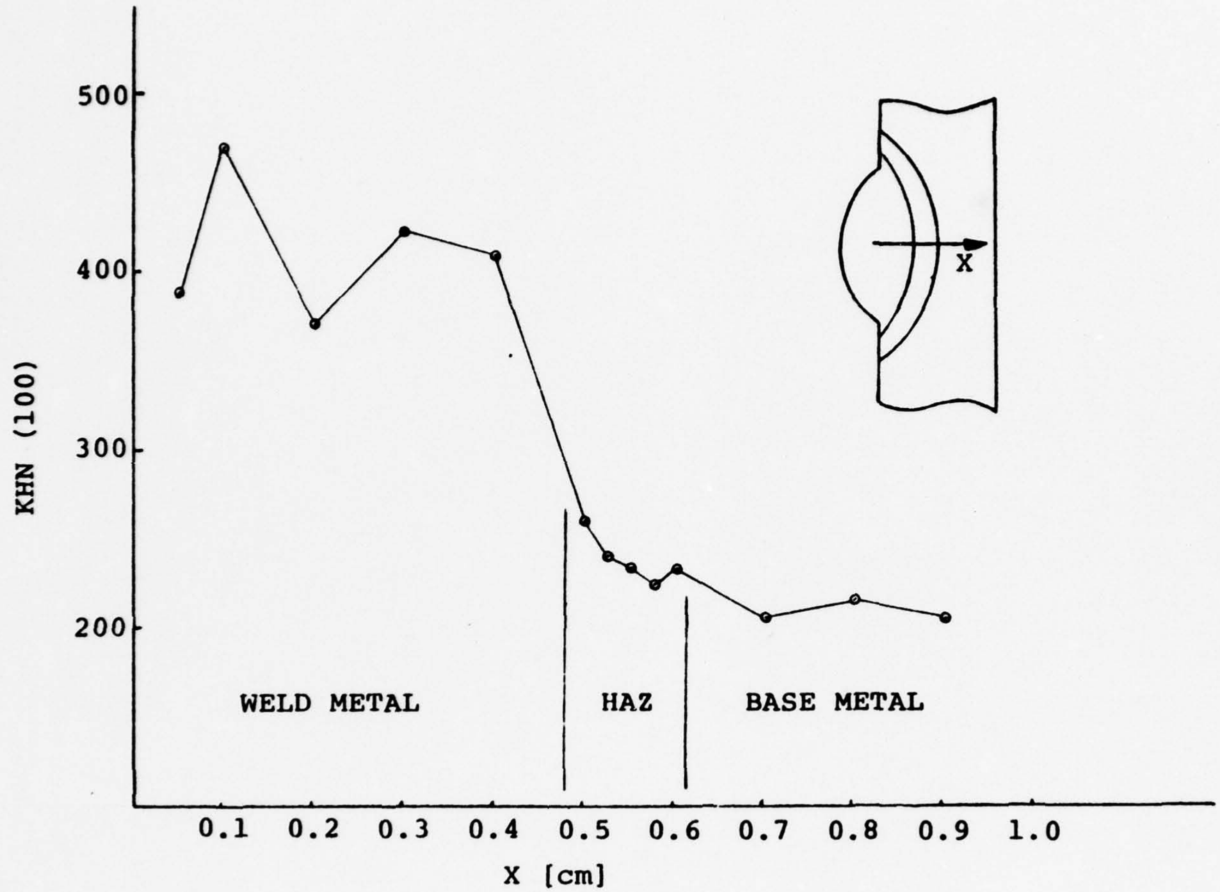


Figure A.9 Microhardness Readings in Underwater Flux-Shielded Weld (250 psig).

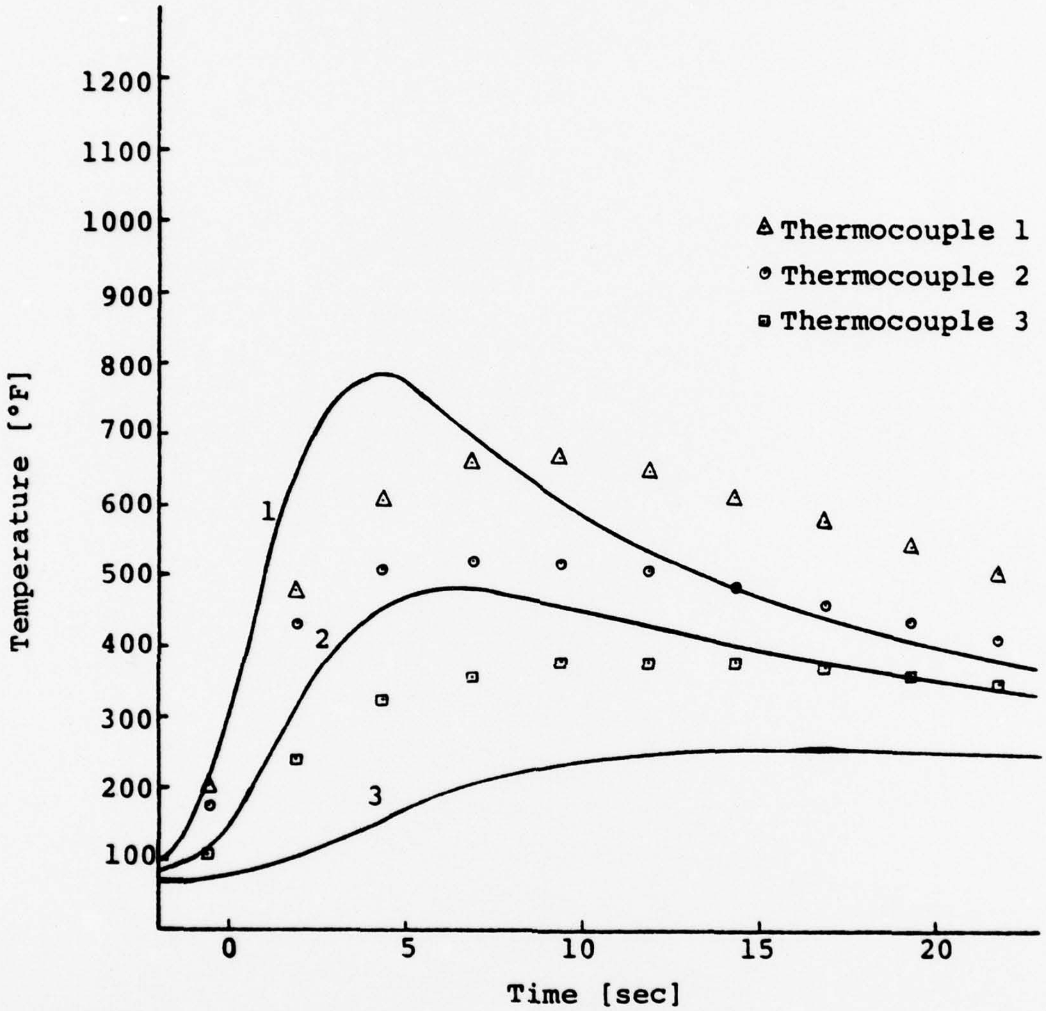


Figure A.10 Calculated Temperature and Measured Temperature in Underwater Flux-Shielded Weld (250 psig).

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